Spectrum of Engineering Sciences
ISSN (e) 3007-3138 (p) 3007-312X
Volume 3, Issue 4, 2025

SMART BATTERY MANAGEMENT SOLUTION FOR ELECTRIC VEHICLES: ENHANCING PERFORMANCE WITH ADVANCED ALGORITHMS AND REAL-TIME MONITORING

Engr. Kashif Abbas[*1], Sadaf Ashraf[2], Bareeha Muqadas[3], Rameez Akbar Talani[4], Muhammad Anwar Ul Haq[5], Mudassar Rafique[6], Muhammad Saad Ali[7], Abdul Qadeer[8], Basit Ahmad[9]

[*1]*Department of Energy Systems Engineering, NFC Institute of Engineering and Technology, Multan, Pakistan*
[2,3]*Department of Physics, NFC Institute of Engineering and Technology, Multan, Pakistan*
[4]*Department of Electrical Engineering, Quaid-e-Awam University of Engineering Science and Technology, Nawabshah*
[5,7,8]*Department of Electrical Engineering, Riphah International University, Islamabad, Pakistan*
[6]*Department of Electrical Engineering, Superior University Lahore, Punjab, Pakistan*
[9]*Department of Electrical Engineering, NFC Institute of Engineering and Technology Multan, Punjab, Pakistan*

[*1]kashif.abbas@engineer.com, [2]sadafashraf6791@gmail.com, [3]bareehamuqadas@gmail.com, [4]rameezakbar@quest.edu.pk, [5]anwarmalik049@gmail.com, [6]mudassarrafique737@gmail.com, [7]saadraja110@gmail.com, [8]abdulqadeer23108@gmail.com, [9]basitahmad3884@gmail.com

DOI: https://doi.org/10.5281/zenodo.15172822

Keywords
Battery Management System, Advanced Algorithms, Predictive Maintenance, Fault Detection, Real-Time Monitoring, Electric Vehicles.

Article History
Received on 01 March 2025
Accepted on 01 April 2025
Published on 07 April 2025

Corresponding Author: *

Abstract
As the adoption of electric vehicles (EVs) continues to grow, the importance of efficient and reliable battery management systems (BMS) becomes increasingly critical. A Smart Battery Management Solution (SBMS) plays a pivotal role in optimizing battery performance, ensuring safety, extending battery life, and enhancing the overall driving experience. This paper explores the integration of advanced algorithms and real-time monitoring techniques in BMS to improve the performance and efficiency of EV batteries. The proposed solution leverages cutting-edge machine learning algorithms for accurate state-of-charge (SOC) estimation, predictive maintenance, and fault detection, while real-time monitoring enables dynamic adjustments to battery parameters, such as temperature, voltage, and current. Additionally, the paper examines the role of thermal management in mitigating risks such as overheating and thermal runaway, further enhancing battery safety and longevity. By combining real-time data analytics, predictive modeling, and intelligent control systems, this research proposes a comprehensive approach to battery management that not only maximizes the efficiency and lifespan of the battery but also contributes to the overall sustainability of electric vehicles. The results underscore the potential for these advanced techniques to revolutionize the way battery systems are managed in EVs, ultimately leading to safer, more efficient, and longer-lasting energy storage solutions.

INTRODUCTION

The global reserves of fossil fuels, such as diesel and petrol, are rapidly depleting due to their extensive use in transportation. The widespread consumption of these fuels generates vast amounts of CO2 annually, leading to harmful environmental effects, including greenhouse gas emissions (GHGE) and global warming [1]. Furthermore, the cost of these fuels is rising sharply, highlighting the urgent need for alternative energy sources in transportation, such as electric vehicles (EVs), new energy vehicles (NEVs), plug-in hybrid electric vehicles (PHEVs), battery electric vehicles (BEVs), and fuel cell electric vehicles (FCEVs). In recent years, rechargeable batteries (RBs) have gained significant attention due to their growing demand in EVs, HEVs, and PHEVs. When paired with renewable energy, these transportation options have the potential to reduce GHGE by up to 40% [2]. However, renewable energy sources like wind, solar, wave, and tidal power are intermittent, requiring the integration of energy storage systems (ESS) to ensure a stable and reliable supply to consumers. Countries such as the United States, Japan, China, and Germany have shown significant interest in improving RB performance and have achieved notable advancements. Various energy storage technologies, including lead-acid, lithium-ion (Li-ion), sodium nickel chloride (NaNiCl), vanadium redox flow batteries (VRFB), nickel-cadmium (NiCd), zinc-bromine flow batteries (ZBFB), and sodium-sulfur (NaS) batteries, have been increasingly adopted for transportation in recent years [3]. Among these, the Li-ion battery stands out for its high reliability, power density, long lifespan, energy density, low discharge rate, and efficiency. Additionally, the declining cost of Li-ion batteries has made them more accessible, further driving their adoption in the EV industry and contributing to the growth of the Li-ion battery market [4].

An effective battery management system (BMS) is crucial in electric vehicles (EVs) to ensure the safe, reliable, efficient, and durable operation of a Li-ion battery, especially when interacting with the electric grid and navigating challenging driving conditions. Additionally, a well-designed BMS monitors key battery states, including the state of available power (SOP), state of charge (SOC), state of life (SOL), and state of health (SOH) [5]. It tracks parameters such as battery voltage, current, and temperature to prevent overcharging or overdischarging. These monitored values are used to estimate the Li-ion battery's various states [6]. Accurate estimation of the SOC has long been a significant concern in BMS design for EVs. Precise SOC measurements not only help assess the battery's reliability but also provide vital data, such as the remaining energy or usable time, which are essential for determining the vehicle's range or the battery's remaining power. Moreover, accurate SOC estimation helps protect the Li-ion battery from overcharging and overdischarging [7]. Given that the Li-ion battery is a complex, nonlinear electrochemical system subject to variations in factors like charge-discharge current, aging, and temperature, estimating the SOC is a challenging task, as it cannot be directly measured using conventional physical sensors. As a result, SOC estimation for Li-ion batteries remains a hot research topic, with numerous estimation techniques being explored in recent years. Figure 1 illustrates the growing trend of research publications on SOC estimation for Li-ion batteries over the past decade.

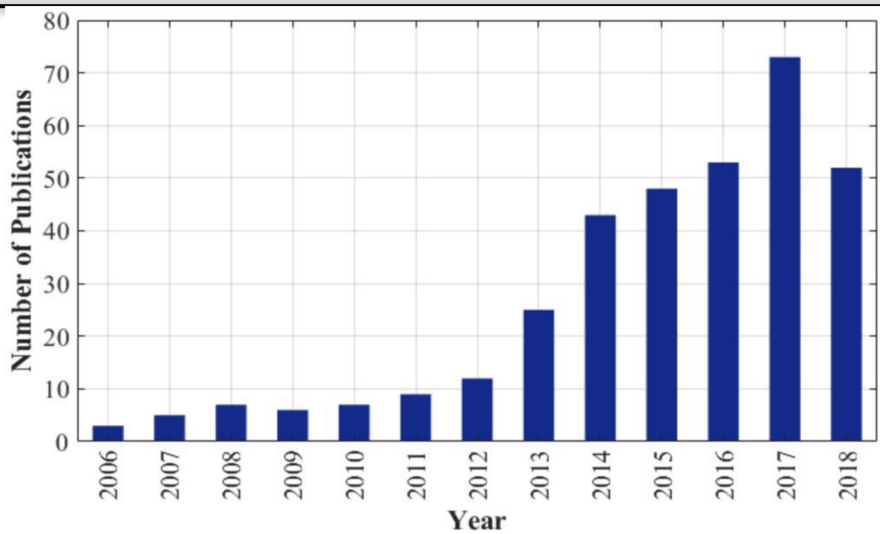

Figure 1. Number of publications on SOC estimation of Li-ion batteries per year [8].

This review paper discusses working and advantages of the Li-ion battery in EVs over other energy storage systems. The general working of an effective BMS is presented in detail. This review paper classifies the reported Li-ion battery SOC estimation techniques in different categories according to their nature. By combining these advanced techniques, this study proposes a comprehensive approach to battery management that maximizes battery efficiency, extends its lifespan, and enhances the sustainability of electric vehicles. The findings have the potential to revolutionize the way battery systems are managed in EVs, paving the way for safer, more efficient, and environmentally friendly transportation solutions.

1- Research Objective:

The primary objective of this research is to explore and develop a Smart Battery Management Solution (SBMS) that can enhance the performance, safety, and lifespan of electric vehicle (EV) batteries. Specifically, the key objectives of this paper are:

1. **Optimization of Battery Performance**: To design and implement advanced algorithms for accurate state-of-charge (SOC) estimation and predictive maintenance, ensuring better management of energy storage and improving overall battery efficiency in EVs.
2. **Real-Time Monitoring and Adaptive Control**: To integrate real-time monitoring techniques for continuously tracking and adjusting critical battery parameters such as temperature, voltage, and current, ensuring optimal performance under varying driving conditions.
3. **Thermal Management Improvement**: To develop strategies for effective thermal management that mitigate risks like overheating and thermal runaway, enhancing the safety and longevity of EV batteries.
4. **Fault Detection and Diagnostics**: To incorporate intelligent fault detection algorithms that can identify potential battery issues in real-time, reducing the likelihood of failure and enabling predictive maintenance to extend battery life [9].
5. **Sustainability and Efficiency**: To evaluate the potential of SBMS in improving the overall sustainability of electric vehicles by maximizing battery life and performance, thereby reducing the need for frequent replacements and promoting eco-friendly transportation.
6. **Future Integration with Emerging Technologies**: To explore the integration of SBMS with next-generation battery technologies, edge computing, and cybersecurity measures to ensure scalability, robustness, and secure operation of EVs in an increasingly connected world.

2- Energy Storage Systems for EVs

EVs consist of four main parts: an energy storage system (battery), mechanical transmission system, motor, and power converter [10]. Many energy storage systems are available, such as lead-acid, NaS, NaNiCl, NiCd, VRFB, ZBFB, and Li-ion. Table 1 lists the properties of the aforementioned batteries. Only ambient temperature batteries have been considered in EVs for safe and reliable operation.

Table 1. Properties of the different types of energy storage systems [11].

Battery Type	Energy Density (Wh/L)	Power Density (W/L)	Nominal Voltage (V)	Life Cycle	Depth of Discharge (%)	Round Trip Efficiency (%)	Estimated Cost (USD/kWh)
Lead-acid	50–80	10–400	2.0	1500	50	82	105–475
NaS	140–300	140–180	2.08	5000	100	80	263–735
NaNiCl	160–275	150–270	-	3000	100	84	315–488
NiCd	60–150	80–600	1.3	2500	85	83	-
VRFB	25–33	1–2	1.4	13,000	100	70	315–1050
ZBFB	55–65	1–25	1.8	10,000	100	70	525–1680
Li-ion	200–400	1500–10,000	4.3	10,000	95	96	200–1260

Table 1 shows that among all the storage devices, the VRFB has the highest life cycle. The Li-ion battery has the highest energy and power densities as compared to the others. In addition, the cost, life cycle, and nominal voltage of the battery are also critical factors. The nominal voltage of a cell is a critical point because it decides the quantity of single cells required in a battery pack for safe and reliable operation. The Li-ion battery appears to be a better option because of its energy density, lifespan, nominal voltage, power density, and cost. Figure 2 presents a spider chart of the different cell chemistries for a better understanding and comparison [12].

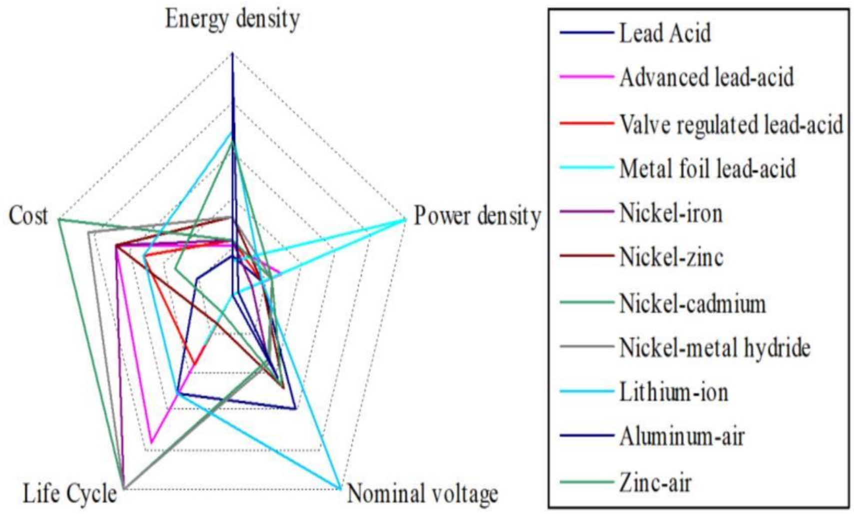

Figure 2. Spider chart for the different battery chemistries [12].

3- Lithium Ion Battery

Figure 3 presents the simplified working diagram of a Li-ion battery. The Li-ion cell is made of a positive electrode (anode), negative electrode (cathode), a separator, and two current collectors. Li^+ is transferred from the anode to the cathode through an electrolytic separator to complete the discharging cycle. The negative electrode is generally formulated from graphite and the anode general contains one of the following materials: Li-ion manganese oxide (LMO), Li-iron-phosphate (LFP), and Li-nickel-manganese-cobalt-oxide (LNMC). Diethyl carbonate or ethylene carbonate are used as the electrolyte. Aluminum and copper are used as positive and negative current collectors, respectively. The chemical reactions of LMO/graphite are reported as an example of both charging discharging [13].

For charging:

$$Li_bMn_2O_4 \rightarrow Li_b{-}aMn_2O_4 + aLi^+ + ae^-$$

$$Li_0C_6 + aLi^+ + ae^- \longrightarrow LixC_6$$

For discharging:

$$Li_b{-}aMn_2O_4 + aLi^+ + ae^- \longrightarrow Li_bMn_2O_4$$

$$LixC_6 \rightarrow Li_0C_6 + aLi^+ + ae^-$$

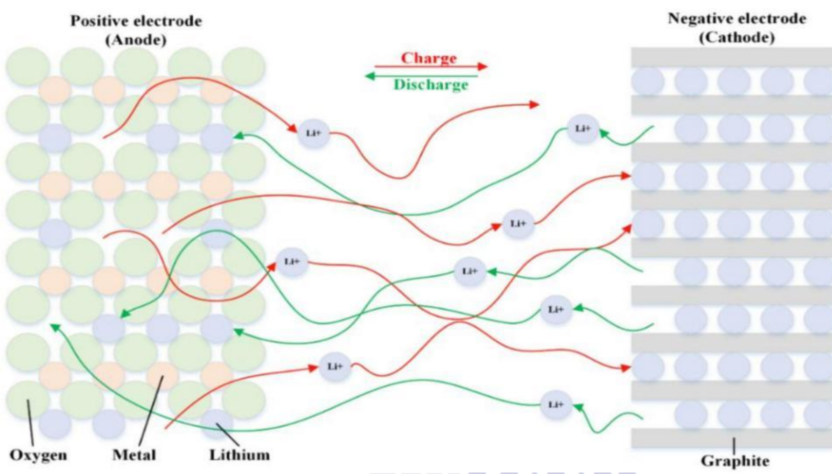

Figure 3. Schematic diagram of the Li-ion battery during the charging and discharging condition.

Different chemistries of Li-ion battery have been reported in the literature [14]. Table 2 compares the different types of Li-ion battery.

Table 2. Properties of the different types of Li-ion battery [15].

Type	Energy Density (Wh/kg)	Power Density (W/kg)	Life Cycle (100% DOD)	Estimated Cost (US$/kWh)	Safety	Maturity
LMO	160	200	≥2000	~360	Good	Commercial
LFP	120	200	≥2500	~360	Good	Commercial
LNMC	200	200	≥2000	~360	Good	Commercial
Li-titanate oxide	70	1000	≥10,000	~860	Good	Demo
Li-sulfur	500	-	~100	-	Good	R&D stage

Although Li-ion battery is the best choice for EVs, it still needs a reduction in its capital cost along with improving performance and high life cycle. The reduction in its capital cost can be achieved in different ways, such as manufacturing and technology perspectives. A lot of efforts have been made to improve the round-trip efficiency and depth of discharge of Li-ion battery [16]. According to a report, the reduction in the capital cost of Li-ion battery will be 77–574 USD/kWh from 200–1260 USD/kWh, the improvement in the energy density will be 200–

735Wh/L, and the round-trip efficiency will increase 2% till 2030 [17].

4- Battery Management System (BMS) for EVs:

Lithium-ion batteries (LIBs) are becoming increasingly powerful and serve as a key alternative to internal combustion engine (ICE) vehicles, contributing to clean transportation globally. Hybrid electric vehicle (HEV) and battery electric vehicle (BEV) systems are expected to have a positive impact on both the global economy and the environment [18]. As EV technologies evolve, there is a growing need for systems that enhance operational efficiency, ensure safe functioning, and protect the energy storage system (ESS). The Battery Management System (BMS) is responsible for overseeing the ESS, transmission, control, and management aspects related to the EV, including tasks such as charge equalization, battery cell voltage regulation, input/output voltage control, protection, and error diagnostics. Some of the key functions and specifications of the BMS are illustrated in Figure 4 [19]. The BMS also monitors and manages the battery's charging status and characteristics, controlling both the charge and discharge cycles as well as the battery pack's load demand. It calculates the voltage levels of each lithium-ion cell to prevent overcharging or undercharging. To optimize battery performance and lifespan, the BMS employs cell balancing techniques, ensuring charge/voltage equalization. It also tracks the temperature of the cells at various stages, manages the power converter, and operates the cells in a way that maintains their health and safety, even under high temperatures [20]. The cell protection mechanism shields the cells from risks such as short circuits, overloads, and current/voltage stresses over time. Within the EV system, the BMS analyzes and monitors energy storage distribution and identifies potential faults. Key specifications include current and voltage monitoring of LIB cells, charge/discharge control estimation and protection, cell equalization, temperature, power, and heat management, data storage and acquisition, communication and networking, as well as fault assessment and diagnosis.

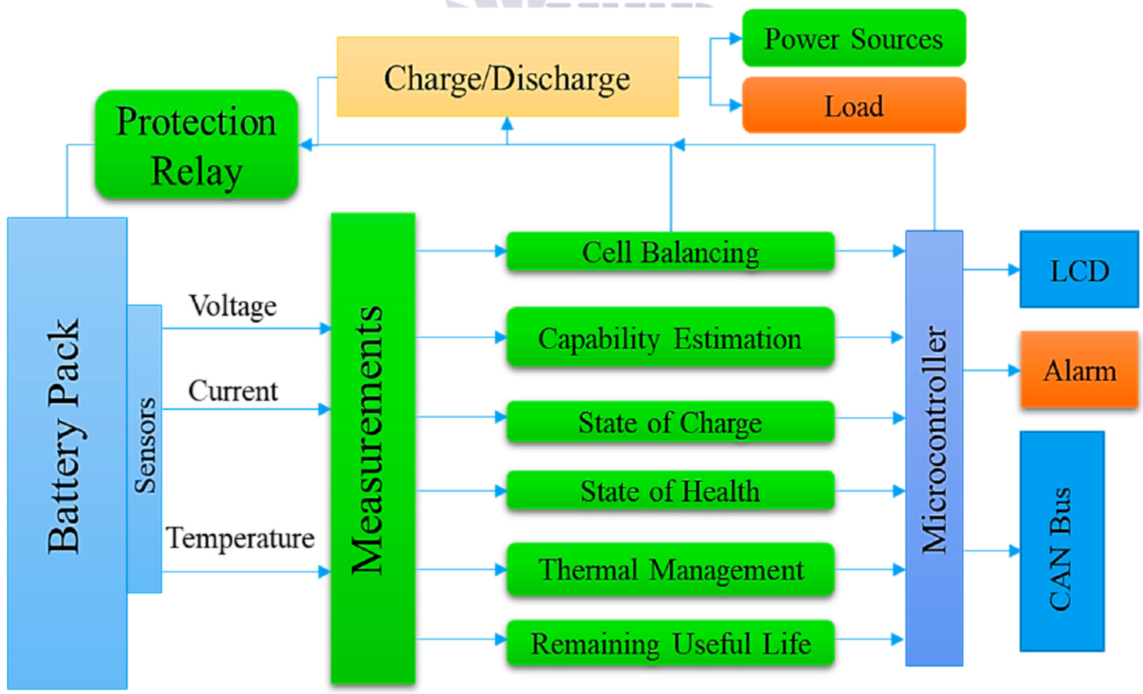

Figure 4. Battery management system, adapted from [21].

5.1. Current and Voltage Monitoring in the Li-Ion Battery Cell

Electric vehicles (EVs) are tightly integrated with lithium-ion battery (LIB) packs, where the behavior of the battery cells can vary during operation. Continuous monitoring of the cells is crucial to assess their state. The results of this monitoring play a key role in optimizing energy management, power delivery, and ensuring safety. The monitoring system oversees various aspects, including cell performance during both charge and discharge cycles, protection against overcharging and undercharging, temperature and heat regulation, fault detection, data acquisition, connectivity, and assessment [22]. LIBs provide a steady voltage and current during discharge, but fluctuations in cell current and voltage can lead to damage or even explosion. Therefore, it is essential to regulate the voltage and current levels during operation to protect the cells from overcharging or undercharging [23]. Additionally, the voltage and current conditions of the battery pack are displayed for further analysis and management.

5.2. Estimation and Protection of LIB Charge/Discharge Control

LIBs' efficiency and development depend on the charge's state and the discharge situations. The optimal conditions for LIB competency enhance battery energy formation and a flexible life cycle. The conventional charge and discharge panels reduce the memory effect and lengthen the battery's discharge duration. LIBs are discharged by CC–CV (constant current and constant voltage) load, the DCM (discontinuous current mode), and PI (proportionally integrated) controller operations, including the state of feature (SOF), the state of charge (SOC), the state of health (SOH), and remaining useful life (RUL) [24-29]. The SOC indicates the charging–discharging and depth condition of LIBs. The SOC will be measured and examined with several methods, i.e., open-circuit voltage (OCV), Coulomb counting (CC), electromotive Force (EMF), internal resistance, electrochemical impedance spectroscopy, model-based SOC estimation, unscented Kalman filter, extended Kalman filter, Kalman filter (KF), sigma point Kalman filter, H∞ filter, particle filter recursive least square, fuzzy logic (FL), neural network (NN), support vector machine (SVM), sliding mode observer, genetic algorithm, non-linear observers, proportional-integral observer, bi-linear interpolation, hybrid method, and impulse response [30]. A battery's state of health (SOH) is determined by its power density, internal impedance, and self-discharge rate. The SOH demonstrates the overall battery performance. The open-loop technique is used to evaluate the SOH. It depends on the durability model, which accepts the mechanism of lithium-ion loss, side reactions, capacity, internal resistance, and the close-loop battery model for parameter detection. The SOH will be measured and examined with a process, i.e., CC, OCV, impedance spectroscopy, KF, particle filter, least square, FL, NN, SVM, sample entropy, and probability density function [31]. The SOF identifies the actual condition of the battery by determining the output ratio of the battery's existing efficiency in EV systems. The charge/discharge profile of the battery can be calculated, determining SOH, SOC, SOF, and operating temperature. The RUL can measure the SOH of the battery. There has been little work done on the estimation of the RUL. Herein, we present some RUL measured and examined with a process, i.e., adaptive filter technique, intelligent techniques, stochastic technique, Bayesian, naïve Bayes, artificial NN, SVM, particles swim optimization, etc. In EVs, LIB cells are used as ESS, connected in serial and parallel combinations on the battery pack. The stored energy of the ESS is used to drive the motor and other systems in the EV and is charged by the power supply from the outside [32-36]. A sequential charge–discharge cycle causes pressure and charge imbalance between battery cells due to the diversity of their physical properties. Unbalanced charging profiles are a discrepancy in surviving systems due to temperature effects, manufacturing defects, and cell aging, which reduce ESS's overall efficiency and reliability. Over-discharge can degrade the battery's chemical components and shorten its lifespan. In addition, overcharging might result in cell explosion [36-39]. The BMS can halt the charge and discharge of the battery when it is not in use state or delivering electricity. Therefore, it is essential to protect batteries and extend their storage capacity to their operating rating [40].

5.3. Cell Equalization

Battery energy storage systems (BESS) are becoming more prevalent in electric vehicle (EV) applications due to their numerous advantages, including quick response to demand, flexibility in installation locations, and short construction time [41]. As a result, BESS positively impacts the electrical power system by supporting functions such as voltage and frequency regulation, black-start capability, standing reserves, renewable energy integration, peak shaving, load leveling, and improving power quality [42]. In BESS, battery cells are arranged in series or parallel strings to meet the required power output. However, an imbalance in the state of charge (SOC) of the cells is common in BESS, which can occur due to both internal and external factors. Causes of cell imbalance include manufacturing defects, varying self-discharge rates, internal impedance, and differences in charge storage capacity [43]. External factors, such as temperature fluctuations, can also lead to SOC imbalances, exacerbated by variations in self-discharge rates during the charge and discharge cycles of unequal cell strings. Over the past few decades, various cell-balancing techniques have been proposed to address these issues, which can be broadly categorized into two main types: active balancing and passive balancing. These techniques are distinguished by their energy storage elements, energy utilization methods, and approaches to balancing, as shown in Figure 5.

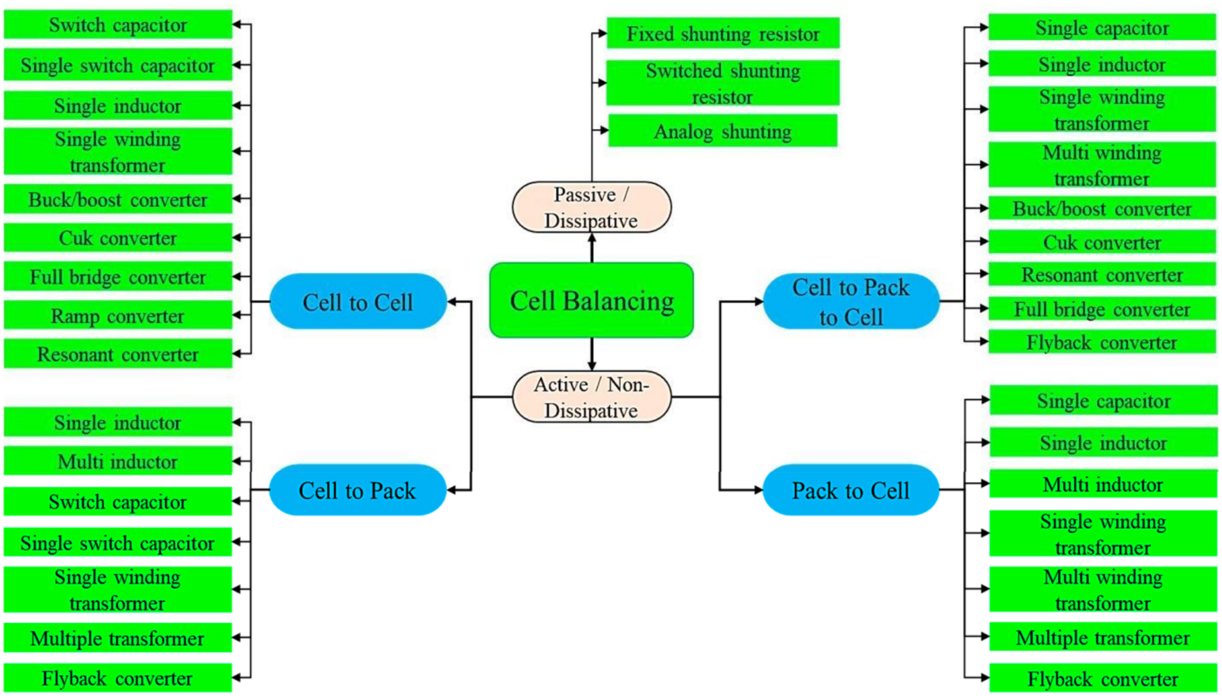

Figure 5. Cell balancing topology [44].

5.4. Temperature, Power, and Heat Management

Efficient and balanced power distribution remains a significant challenge for electric vehicles (EVs), as minimizing power loss and avoiding damage are key goals. Without proper power management, the overall performance of the system is compromised. Additionally, factors such as various types of electronic equipment, irregular operation of machinery, and unreliable power supply contribute to the reduced effectiveness of the battery energy storage system (BESS). Implementing power management and control during the EV charging process, using an intelligent management system, is an effective approach to stabilize power supply and optimize performance. To ensure system protection, longevity, and efficiency, it is crucial to regulate power based on factors like state of charge (SOC), state of health (SOH), and battery aging [45]. This approach minimizes power loss and enhances the automated control and management of EV systems. Temperature regulation is another important aspect of the energy storage system, as it helps maintain the lithium-ion battery (LIB) within its thermal range by controlling heating and cooling. Continuous temperature monitoring is essential to prevent overheating and potential explosions. The LIB pack must be compatible with the EV, and the Battery Management System (BMS) controls the onboard cooling and heating systems [46]. A LIB consists of an electrode, electrolyte, and separator, all enclosed in a shell. For optimal performance and safe operation, the LIB's functional temperature range is between 15°C and 45°C. Below 15°C, the LIB may fail to perform properly, as electrochemical reactions are hindered [47]. At low temperatures during charging, lithium dendrites can form and damage the separator, causing short circuits. Additionally, if the voltage rises beyond the cutoff level, capacitive loss occurs. On the other hand, temperatures above 40°C pose risks to the smooth operation of the LIB, potentially causing imbalances in its electrochemical properties, which can lead to explosions. These explosions happen when the internal chemicals release gases like CO, C2H2, and H2S, and when a short circuit occurs in the LIB's internal power circuit. Various thermal management methods are illustrated in Figure 7, with further details available in references [48-50].

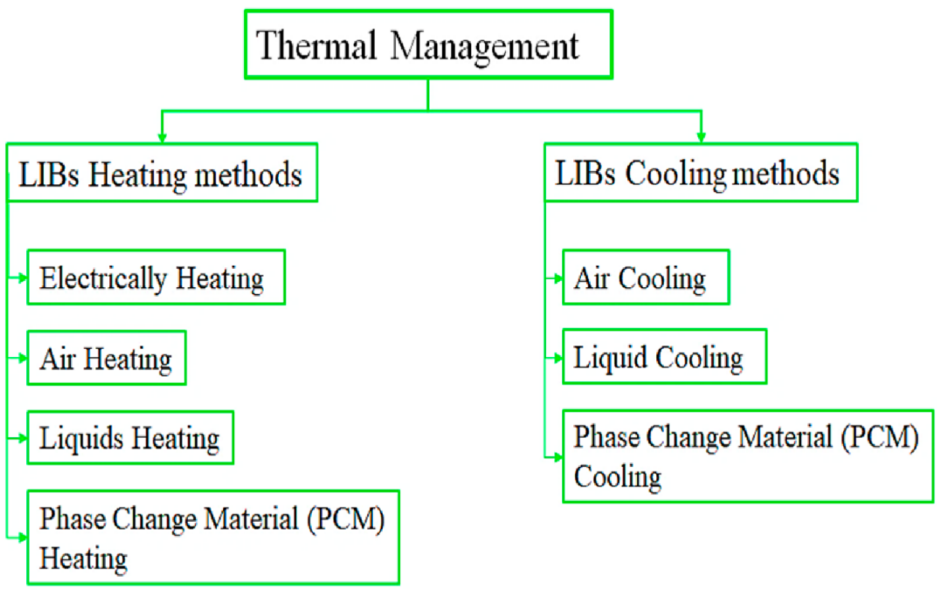

Figure 6. Taxonomy of thermal management system [51].

5.5. Data Storage and Acquisition: Communication and Networking

Electric vehicle (EV) systems integrate various subsystems and networks within the vehicle. The performance of an EV depends on the electronic tracking, configuration, and adjustment of the Battery Management System (BMS), which can also detect EV charging stations and estimate the driving range [52]. The BMS monitors battery data from the EV's energy storage system, such as voltage and state of charge (SOC) from the lithium-ion battery (LIB), temperature, charge and discharge rates, and program control. It processes and transmits the stored data related to cell parameters, fault diagnostics, thermal management, and monitoring through the controller. The EV's central controller is linked to several control units that calculate the BMS's operation and deliver consistent decision outputs [53]. The data acquisition systems gather data from the energy storage system (ESS) and assess its condition using the BMS. These acquisition systems also include various instruments and applications. The LIB data acquisition system is compatible with digital and analog sensors, such as pressure or gas sensors. Understanding the internal status of the cells is essential for creating accurate cell models, as well as for assessing cell performance within a module [54]. Inadequate temperature management can lead to uneven aging and rapid deterioration of the cells. To monitor temperature, a set of seven thermistors was installed to measure core temperature, combining these readings with cell current via a bus bar, attached sensors, and voltage sensor data [55]. The development of smart cells also includes power line communication (PLC) circuits. The MODBUS TCP protocol enables a Wi-Fi connection between the EV and a computer, allowing all signals to be transmitted wirelessly from the EV to the computer [56]. The signals gathered from the data acquisition prototype were used to verify its operational accuracy by comparing them with data from a "NI myDAQ" device and observing the changes in the measured quantities during battery discharge to assess the system's performance. Data storage and acquisition facilitate the identification of the optimal operating conditions and preventive maintenance requirements for the LIB [57].

5.6. Fault Assessment and Diagnosis

Energy storage systems (ESS) may face several challenges, including excessive flow, insufficient charge, voltage stress, and extreme temperature conditions. The Battery Management System (BMS) also monitors issues related to system maintenance, power faults, coding errors, supply shortages, availability, and breakdowns [58]. Additionally, the BMS is responsible for detecting anomalies based on system indicators and making appropriate decisions. Advanced measurements require innovations, system knowledge, tight monitoring, team collaboration, documentation, and other tools. Lithium-ion batteries (LIBs) are assessed using control signals, research models, and expertise [59]. Fault diagnosis helps simplify the process and improve the performance of LIBs within the energy storage system. The LIB is a complex, nonlinear, time-varying system with multiple inconsistencies, and diagnosing faults in LIBs can be challenging, especially when issues are not immediately visible. Voltage fluctuations are a common indicator of faults, making voltage inconsistency monitoring essential for ensuring the safe and reliable operation of LIBs in electric vehicles (EVs) [60]. The entropy method, which doesn't rely on precise analytical models or expert knowledge and overlooks system structure and fault complexities, has raised significant interest. For more information on fault diagnosis, additional details can be found in reference [61]. The BMS collects data on the battery, power input, performance, user interfaces, sensors, and energy storage frameworks. As a result, implementing Battery Management Diagnostics (BMD) is crucial for enhancing EV applications, prolonging the energy storage system's life, and ensuring reliable power, efficiency, and accurate energy assessment [62].

5- Future Work:

While the integration of advanced algorithms and real-time monitoring techniques has demonstrated significant potential for improving the performance, safety, and longevity of electric vehicle batteries, there are still several avenues for further research and development. Future work in this domain can focus on the following areas:

1. **Enhanced Machine Learning Models for Battery Performance Prediction**
   Although machine learning algorithms for state-of-charge (SOC) estimation and predictive maintenance have shown promise, further research is needed to refine these models for even more accurate predictions [63]. In particular, deep learning and reinforcement learning techniques could be explored to better account for the complex, non-linear behavior of battery cells under various operating conditions. Additionally, improving model generalization across different battery chemistries and aging conditions will be crucial for creating more robust systems [64].
2. **Integration with Next-Generation Battery Technologies**
   The ongoing development of next-generation battery technologies, such as solid-state batteries or lithium-sulfur batteries, presents an exciting opportunity for SBMS advancements [65]. Future research should focus on adapting existing battery management solutions to support these new chemistries, which may have different performance characteristics, degradation profiles, and safety concerns. Tailoring BMS algorithms to the unique requirements of next-gen batteries will be essential for optimizing their efficiency and safety.

3. **Real-Time Optimization Using Edge Computing**
   Real-time data processing plays a critical role in the performance of SBMS. While cloud computing has been widely used for data analytics and monitoring, edge computing offers the potential to process data closer to the battery system, reducing latency and enabling faster decision-making [66]. Future work could explore how edge computing can be integrated into SBMS, allowing for more responsive and efficient battery management, particularly in scenarios involving high-rate charge/discharge or fluctuating driving conditions.

4. **Improved Thermal Management Strategies**
   Although the role of thermal management in preventing overheating and thermal runaway has been explored, further work is needed to develop more efficient and adaptive cooling systems [67]. Future research could focus on advanced thermal management solutions that integrate real-time sensor data, such as temperature gradients within the battery pack, to dynamically adjust cooling or heating strategies. The use of phase-change materials or micro-channel heat exchangers could also be investigated to improve thermal efficiency and minimize the risk of battery degradation due to excessive heat [68].

5. **Cybersecurity and Data Privacy in SBMS**
   As EVs become increasingly connected, ensuring the cybersecurity of Smart Battery Management Systems will become paramount. Future work should address potential vulnerabilities in SBMS, especially regarding the transmission of real-time data between the vehicle, the cloud, and charging infrastructure [69]. Research into robust encryption methods, secure communication protocols, and anomaly detection algorithms will be essential to prevent malicious attacks or unauthorized access to sensitive battery data.

6. **Integration with Vehicle-to-Grid (V2G) Technologies**
   Another promising area for future research lies in the integration of SBMS with Vehicle-to-Grid (V2G) technologies, which enable EVs to supply power back to the grid [70]. The development of intelligent BMS capable of dynamically managing energy flow between the vehicle and the grid could contribute to grid stability, improve energy efficiency, and enhance the sustainability of the transportation ecosystem. Research should focus on optimizing BMS algorithms for bi-directional energy flow, while ensuring battery longevity and vehicle performance [71].

7. **User-Centric BMS Features**
   Finally, future work should explore the development of user-centric features within SBMS. These could include advanced user interfaces that provide real-time insights into battery health, performance, and remaining range, or predictive notifications for optimal charging and maintenance schedules [72]. Additionally, incorporating vehicle-specific usage patterns and user preferences could further personalize battery management, creating a seamless and intuitive experience for EV owners.

6- Conclusion:

In conclusion, this paper explored the role of Smart Battery Management Solutions (SBMS) in enhancing the performance, safety, and lifespan of electric vehicle (EV) batteries. By integrating advanced algorithms for accurate state-of-charge (SOC) estimation, predictive maintenance, and fault detection, SBMS can optimize battery efficiency. Real-time monitoring of critical parameters like temperature, voltage, and current ensures dynamic adjustments, improving overall battery performance. Additionally, effective thermal management prevents risks like overheating and thermal runaway, boosting battery safety. SBMS provides a comprehensive approach to managing EV batteries, contributing to longer-lasting, more efficient, and safer energy storage systems. As technology advances, integrating new battery chemistries, edge computing, and enhanced cybersecurity will further strengthen these systems. Overall, SBMS has the potential to revolutionize battery management, driving the future of electric vehicles towards greater sustainability and performance.

REFERENCES

Ali, A. M., & Söffker, D. (2018). Towards optimal power management of hybrid electric vehicles in real-time: A review on methods, challenges, and state-of-the-art solutions. *Energies*, *11*(3), 476.

Abdul-Hak, M., Al-Holou, N., & Mohammad, U. (2011). Predictive intelligent battery management system to enhance the performance of electric vehicle. *Electric Vehicles–Modelling and Simulations*, 365.

Kosuru, V. S. R., & Kavasseri Venkitaraman, A. (2023). A smart battery management system for electric vehicles using deep learning-based sensor fault detection. *World Electric Vehicle Journal*, *14*(4), 101.

Hossain Lipu, M. S., Miah, M. S., Ansari, S., Wali, S. B., Jamal, T., Elavarasan, R. M., ... & Tan, N. M. (2022). Smart battery management technology in electric vehicle applications: Analytical and technical assessment toward emerging future directions. *Batteries*, *8*(11), 219.

Rahimi-Eichi, H., Ojha, U., Baronti, F., & Chow, M. Y. (2013). Battery management system: An overview of its application in the smart grid and electric vehicles. *IEEE industrial electronics magazine*, *7*(2), 4-16.

Lipu, M. H., Miah, M. S., Jamal, T., Rahman, T., Ansari, S., Rahman, M. S., ... & Shakib, M. N. (2023). Artificial intelligence approaches for advanced battery management system in electric vehicle applications: A statistical analysis towards future research opportunities. *Vehicles*, *6*(1), 22-70.

Yang, S., Liu, X., Shen, L., & Zhang, C. (2023). *Advanced Battery Management System for Electric Vehicles* (Vol. 1). Springer.

Kiasari, M. M., & Aly, H. H. (2024). A proposed controller for real-time management of electrical vehicle battery fleet with MATLAB/SIMULINK. *Journal of Energy Storage*, *99*, 113235.

Habib, A. A., Hasan, M. K., Issa, G. F., Singh, D., Islam, S., & Ghazal, T. M. (2023). Lithium-ion battery management system for electric vehicles: constraints, challenges, and recommendations. *Batteries*, *9*(3), 152.

Lipu, M. S. H., Mamun, A. A., Ansari, S., Miah, M. S., Hasan, K., Meraj, S. T., ... & Tan, N. M. (2022). Battery management, key technologies, methods, issues, and future trends of electric vehicles: A pathway toward achieving sustainable development goals. *Batteries*, *8*(9), 119.

Gomozov, O., Trovão, J. P. F., Kestelyn, X., & Dubois, M. R. (2016). Adaptive energy management system based on a real-time model predictive control with nonuniform sampling time for multiple energy storage electric vehicle. *IEEE Transactions on Vehicular Technology*, *66*(7), 5520-5530.

Tabassum, S., Bharathi, M., Peramasani, N., Nagadivya, N., Busetty, B., & Syed, A. S. (2025, January). Enhancing IoT-Enabled Electric Vehicle Battery Performance Monitoring and Prediction using AI Techniques. In *2025 International Conference on Intelligent and Innovative Technologies in Computing, Electrical and Electronics (IITCEE)* (pp. 1-6). IEEE.

Panwar, N. G., Singh, S., Garg, A., Gupta, A. K., & Gao, L. (2021). Recent advancements in battery management system for Li-ion batteries of electric vehicles: future role of digital twin, cyber-physical systems, battery swapping technology, and nondestructive testing. *Energy Technology*, *9*(8), 2000984.

Waseem, M., Ahmad, M., Parveen, A., & Suhaib, M. (2023). Battery technologies and functionality of battery management system for EVs: Current status, key challenges, and future prospectives. *Journal of Power Sources*, *580*, 233349.

El Hadraoui, H., Ouahabi, N., El Bazi, N., Laayati, O., Zegrari, M., & Chebak, A. (2024). Toward an Intelligent diagnosis and prognostic health management system for autonomous electric vehicle powertrains: A novel distributed intelligent digital twin-based architecture. *IEEE Access*.

Nyamathulla, S., & Dhanamjayulu, C. (2024). A review of battery energy storage systems and advanced battery management system for different applications: Challenges and recommendations. *Journal of Energy Storage*, *86*, 111179.

Naresh, V. S., Ratnakara Rao, G. V., & Prabhakar, D. V. N. (2024). Predictive machine learning in optimizing the performance of electric vehicle batteries: Techniques, challenges, and solutions. *Wiley Interdisciplinary Reviews: Data Mining and Knowledge Discovery*, *14*(5), e1539.

Minhas, D. M., Meiers, J., & Frey, G. (2022). Electric vehicle battery storage concentric intelligent home energy management system using real life data sets. *Energies*, *15*(5), 1619.

Komsiyska, L., Buchberger, T., Diehl, S., Ehrensberger, M., Hanzl, C., Hartmann, C., ... & Endisch, C. (2021). Critical review of intelligent battery systems: Challenges, implementation, and potential for electric vehicles. *Energies*, *14*(18), 5989.

Kim, E., Lee, J., & Shin, K. G. (2013, April). Real-time prediction of battery power requirements for electric vehicles. In *Proceedings of the ACM/IEEE 4th International Conference on Cyber-Physical Systems* (pp. 11-20).

Li, B., Kisacikoglu, M. C., Liu, C., Singh, N., & Erol-Kantarci, M. (2017). Big data analytics for electric vehicle integration in green smart cities. *IEEE Communications Magazine*, *55*(11), 19-25.

Liu, W., Placke, T., & Chau, K. T. (2022). Overview of batteries and battery management for electric vehicles. *Energy Reports*, *8*, 4058-4084.

Mulpuri, S. K., Sah, B., & Kumar, P. (2025). Intelligent Battery Management System (BMS) with End-Edge-Cloud Connectivity-A Perspective. *Sustainable Energy & Fuels*.

Saidulu, I., Monda, K., Purushotham, S., Kumar, K. S., & Lydia, J. (2024, December). A Smart Battery Management System (BMS) Development for Electric Vehicles to Improve Energy and Power Management Structure. In *2024 International Conference on Innovative Computing, Intelligent Communication and Smart Electrical Systems (ICSES)* (pp. 1-6). IEEE.

You, G. W., Park, S., & Oh, D. (2016). Real-time state-of-health estimation for electric vehicle batteries: A data-driven approach. *Applied energy*, *176*, 92-103.

Yang, S., Zhang, Z., Cao, R., Wang, M., Cheng, H., Zhang, L., ... & Liu, X. (2021). Implementation for a cloud battery management system based on the CHAIN framework. *Energy and AI*, *5*, 100088.

Yang, C., Zha, M., Wang, W., Liu, K., & Xiang, C. (2020). Efficient energy management strategy for hybrid electric vehicles/plug-in hybrid electric vehicles: review and recent advances under intelligent transportation system. *IET Intelligent Transport Systems*, *14*(7), 702-711.

Lv, Z., Qiao, L., Cai, K., & Wang, Q. (2020). Big data analysis technology for electric vehicle networks in smart cities. *IEEE Transactions on Intelligent Transportation Systems*, *22*(3), 1807-1816.

Rao, V. S., Sajja, G. S., Manur, V. B., Arandhakar, S., & Krishna, V. M. (2025). An exploratory study on intelligent active cell balancing of electric vehicle battery management and performance using machine learning algorithms. *Results in Engineering*, *25*, 104524.

Suresh, K. (2024, October). An Artificially Intelligent Battery Management System. In *2024 International Conference on Power, Energy, Control and Transmission Systems (ICPECTS)* (pp. 1-5). IEEE.

Das, O., Zafar, M. H., Sanfilippo, F., Rudra, S., & Kolhe, M. L. (2024). Advancements in digital twin technology and machine learning for energy systems: A comprehensive review of applications in smart grids, renewable energy, and electric vehicle optimisation. *Energy Conversion and Management: X*, 100715.

Demirci, O., Taskin, S., Schaltz, E., & Demirci, B. A. (2024). Review of battery state estimation methods for electric vehicles-Part I: SOC estimation. *Journal of energy storage*, *87*, 111435.

Luo, Y., Chen, T., Zhang, S., & Li, K. (2015). Intelligent hybrid electric vehicle ACC with coordinated control of tracking ability, fuel economy, and ride comfort. *IEEE Transactions on Intelligent Transportation Systems*, *16*(4), 2303-2308.

Hu, J., Liu, D., Du, C., Yan, F., & Lv, C. (2020). Intelligent energy management strategy of hybrid energy storage system for electric vehicle based on driving pattern recognition. *Energy*, *198*, 117298.

Lyu, Z., Wu, L., Lyu, M., Yang, J., & Li, X. (2024). Towards an intelligent battery management system for electric vehicle applications: Dataset considerations, algorithmic approaches, and future trends. *Journal of Energy Storage*, *101*, 113827.

Naseri, F., Gil, S., Barbu, C., Cetkin, E., Yarimca, G., Jensen, A. C., ... & Gomes, C. (2023). Digital twin of electric vehicle battery systems: Comprehensive review of the use cases, requirements, and platforms. *Renewable and Sustainable Energy Reviews*, *179*, 113280.

Raj, K. G., Srinivas, T. N., Jeswanth, M. G., & Sundaram, N. M. (2024, July). A Smart and Efficient Cooling System Design for High-Performance Electric Vehicle Battery Packs. In *IOP Conference Series: Earth and Environmental Science* (Vol. 1375, No. 1, p. 012030). IOP Publishing.

Zhang, S., & Xiong, R. (2015). Adaptive energy management of a plug-in hybrid electric vehicle based on driving pattern recognition and dynamic programming. *Applied Energy*, *155*, 68-78.

Shoukat, M. U., Yan, L., Du, C., Raza, M. U. M., Adeel, M., & Khan, T. (2022, October). Application of digital twin in smart battery electric vehicle: Industry 4.0. In *2022 International conference on IT and industrial technologies (ICIT)* (pp. 1-7). IEEE.

Sivaraju, S. S. (2025). Enhancing electric vehicle charging safety and efficiency through hybrid charging systems and intelligent management strategies. *Journal of Energy Storage*, *118*, 116073.

Mahadevan, V., & Vikraman, B. P. (2025). LSTM based battery management systems and FOPID based cooling system strategy for electric vehicles application. *Journal of Energy Storage*, *116*, 115937.

Tirgar, P., Kumar, V. S., Lakhanpal, S., & NK, R. (2025). MLA-Machine Learning Approach for Dependable Battery Condition Monitoring in Electric Vehicles. In *E3S Web of Conferences* (Vol. 619, p. 03020). EDP Sciences.

Tirgar, P., Kumar, V. S., Lakhanpal, S., & NK, R. (2025). MLA-Machine Learning Approach for Dependable Battery Condition Monitoring in Electric Vehicles. In *E3S Web of Conferences* (Vol. 619, p. 03020). EDP Sciences.

Miraftabzadeh, S. M., Longo, M., Di Martino, A., Saldarini, A., & Faranda, R. S. (2024). Exploring the synergy of artificial intelligence in energy storage systems for electric vehicles. *Electronics*, *13*(10), 1973.

Lü, X., Wu, Y., Lian, J., Zhang, Y., Chen, C., Wang, P., & Meng, L. (2020). Energy management of hybrid electric vehicles: A review of energy optimization of fuel cell hybrid power system based on genetic algorithm. *Energy Conversion and Management*, *205*, 112474.

Jamil, H., Naqvi, S. S. A., Iqbal, N., Khan, M. A., Qayyum, F., Muhammad, F., ... & Kim, D. H. (2024). Analysis on the driving and braking control logic algorithm for mobility energy efficiency in electric vehicle. *Smart Grids and Sustainable Energy*, *9*(1), 12.

Teimoori, Z., & Yassine, A. (2022). A review on intelligent energy management systems for future electric vehicle transportation. *Sustainability*, *14*(21), 14100.

Göl, M., Ok, O., Karadağ, V., & Hartavi, A. E. (2024). ACCURATE RANGE PREDICTION IN ELECTRIC VEHICLES: INTEGRATING INTERNAL AND EXTERNAL DATA FOR ENHANCED PERFORMANCE.

Wang, Y., Xu, R., Zhou, C., Kang, X., & Chen, Z. (2022). Digital twin and cloud-side-end collaboration for intelligent battery management system. *Journal of Manufacturing Systems*, *62*, 124-134.

Jamadar, S., & Singaram, G. (2025). Design and development of energy management system for solar electric vehicle with dynamic power split approach. *Australian Journal of Electrical and Electronics Engineering*, *22*(1), 15-26.

Ullah, Z., Ullah, K., Diaz-Londono, C., Gruosso, G., & Basit, A. (2023). Enhancing grid operation with electric vehicle integration in automatic generation control. *Energies*, *16*(20), 7118.

Goddu, H. V., Ejjada, L., & Gara, M. ENHANCING ELECTRIC VEHICLE PERFORMANCE AND SUSTAINABILITY THROUGH ADVANCED ENERGY MANAGEMENT SYSTEMS.

Jamjuntr, P., Techawatcharapaikul, C., & Suanpang, P. (2024). Optimizing Vehicle-to-Vehicle (V2V) Charging in Electric Vehicles by Adaptive Q-learning Implication for Smart Tourism. *Decision Making: Applications in Management and Engineering*, *7*(2), 608-635.

Xing, Y., & Lv, C. (2019). Dynamic state estimation for the advanced brake system of electric vehicles by using deep recurrent neural networks. *IEEE Transactions on Industrial Electronics*, *67*(11), 9536-9547.

Arévalo, P., Ochoa-Correa, D., & Villa-Ávila, E. (2024). Systematic Review of the Effective Integration of Storage Systems and Electric Vehicles in Microgrid Networks: Innovative Approaches for Energy Management. *Vehicles*, *6*(4), 2075-2105.

CHRISTINA, M. J. J., Manibharathi, M., Sampath, V., Sharan, T., & Sivakumar, R. DESIGN AND IMPLEMENTATION OF IOT BASED WIRELESS BATTERY MANAGEMENT SYSTEM FOR ELECTRIC VEHICLES.

Sifakis, N. K., & Kanellos, F. D. (2024). Real Time Multi-Agent based Power Management of Virtually Integrated Microgrids comprising Prosumers of Plugin Electric Vehicles and Renewable Energy Sources. *IEEE Access*.

Shi, D., Zhao, J., Eze, C., Wang, Z., Wang, J., Lian, Y., & Burke, A. F. (2023). Cloud-based artificial intelligence framework for battery management system. *Energies*, *16*(11), 4403.

Fernandez, V., & Pérez, V. (2024). Optimization of electric vehicle charging control in a demand-side management context: a model predictive control approach. *Applied Sciences*, *14*(19), 8736.

Rehan, H. (2024). The Future of Electric Vehicles: Navigating the Intersection of AI, Cloud Technology, and Cybersecurity. *Valley International Journal Digital Library*, 1127-1143.

Sarmah, S. B., Kalita, P., Garg, A., Niu, X. D., Zhang, X. W., Peng, X., & Bhattacharjee, D. (2019). A review of state of health estimation of energy storage systems: Challenges and possible solutions for futuristic applications of li-ion battery packs in electric vehicles. *Journal of Electrochemical Energy Conversion and Storage*, *16*(4), 040801.

Sun, C., Moura, S. J., Hu, X., Hedrick, J. K., & Sun, F. (2014). Dynamic traffic feedback data enabled energy management in plug-in hybrid electric vehicles. *IEEE Transactions on Control Systems Technology*, *23*(3), 1075-1086.

Moreno, J., Ortúzar, M. E., & Dixon, J. W. (2006). Energy-management system for a hybrid electric vehicle, using ultracapacitors and neural networks. *IEEE transactions on Industrial Electronics*, *53*(2), 614-623.

Jujjuvarapu, R. K., & Gaddala, S. C. (2024, September). Data Science Applications in IoT for Electric Vehicles: Leveraging Artificial Intelligence and Machine Learning. In *2024 3rd International Conference for Advancement in Technology (ICONAT)* (pp. 1-6). IEEE.

Zhao, J., Qu, X., Wu, Y., Fowler, M., & Burke, A. F. (2024). Artificial intelligence-driven real-world battery diagnostics. *Energy and AI*, *18*, 100419.

Santhakumar, G., Malavika, V., Sarabheswaran, K., Yusoof, M. F., & Sankar, G. (2024, June). Solar based Wireless Charging and Battery Level Management. In *2024 3rd International Conference on Applied Artificial Intelligence and Computing (ICAAIC)* (pp. 1706-1710). IEEE.

Xiong, R., Duan, Y., Cao, J., & Yu, Q. (2018). Battery and ultracapacitor in-the-loop approach to validate a real-time power management method for an all-climate electric vehicle. *Applied energy*, *217*, 153-165.

Gong, Q., Li, Y., & Peng, Z. R. (2008). Trip-based optimal power management of plug-in hybrid electric vehicles. *IEEE Transactions on vehicular technology*, *57*(6), 3393-3401.

Babu, P. S., V, I., & S, V. (2024). Enhanced SOC estimation of lithium ion batteries with RealTime data using machine learning algorithms. *Scientific Reports*, *14*(1), 16036.

Wu, G., Boriboonsomsin, K., & Barth, M. J. (2014). Development and evaluation of an intelligent energy-management strategy for plug-in hybrid electric vehicles. *IEEE Transactions on Intelligent Transportation Systems*, *15*(3), 1091-1100.

Thirumalaikumari, T., Princy, D. L., Uma, S., Sadaieswaran, R., Malathi, P., & Legapriyadharshini, N. (2024, March). Intelligent Energy Management for Electric Vehicles: Fuzzy Logic and Neural Network Integration. In *2024 10th International Conference on Advanced Computing and Communication Systems (ICACCS)* (Vol. 1, pp. 1269-1274). IEEE.

Kyriakou, D. G., Kanellos, F. D., & Ipsakis, D. (2024). Multi-agent-based real-time operation of microgrids employing plug-in electric vehicles and building prosumers. *Sustainable Energy, Grids and Networks*, *37*, 101229.