

Sustainable Battery Management for Electric Vehicles Using Fog Computing: A Framework for Efficient Monitoring and Lifecycle Optimization

S.Karthika

Dr.K.Juliana Gnanaselvi

Research Scholar,

Assistant Professor,

Department of Computer Science.

Department of Computer Science,

Rathinam College of Arts and Science.

Rathinam College of Arts and Science.

Email id: karthisivaprakash27@gmail.com

Abstract - As EVs become more popular, the need for effective and eco-friendly battery management systems has escalated to ensure reliable performance, prolong battery life, and minimizes environmental impact. In the case of a conventional cloud-based battery management system, communication delays, higher bandwidth usage or laggy responses may occur during crucial battery statuses. To overcome these challenges, this paper introduces a Fog enabled Sustainable Battery Management Framework (FSBMF) which combines the technologies of battery sensing, fog computing, cloud computing, and user applications into a single platform for enabling intelligent battery monitoring and life-time management. The proposed framework allows battery data to be processed locally at the fog nodes in real time, which enables the estimation of the State of Charge (SOC), State of Health (SOH), and Remaining Useful Life (RUL) estimation, as well as thermal management, charging optimization, and fault detection. The cloud layer carries out long-term battery degradation analysis, historical data storage, battery lifecycle assessment, and battery sustainability evaluation while the application layer helps to monitor, maintain, and guide battery recycling with recommendations. Through simulation-based performance evaluation, it has been proven that the proposed framework can improve the accuracy of battery state estimation, reduce communication delay and response time, increase charging efficiency and help achieve sustainable utilization of batteries by providing charging

suggestions, second-life applications, and recycling suggestions, etc. The findings show that the proposed system is a promising solution for next-generation EV battery management systems, as it offers significant benefits in terms of operational reliability, energy efficiency, and lifecycle sustainability.

Keywords: Electric Vehicles, Battery Management System, Fog Computing, Sustainable Battery Management, State of Charge, State of Health, Remaining Useful Life, Thermal Management, Energy Efficiency, and Battery Lifecycle Management.

1. Introduction

Electric vehicles (EVs) are emerging as a promising alternative to traditional internal combustion engine vehicles, with the global shift toward sustainable transport picking up significant momentum. The impact of climate change, greenhouse gas emissions, air pollution and dwindling fossil fuel resources have led to increased investments by governments, industries and researchers in cleaner mobility solutions. The battery is a critical part of an EV's energy storage system, influencing a vehicle's range, performance, charging time, safety, and cost-effectiveness. Therefore, sustainability of batteries is among the most critical research directions in the field of today's electric mobility.

The Lithium-ion batteries are the most common type of batteries used in EVs, owing to their high energy density, relatively low self discharge and long cycle life. However, there are a number of technical and environmental problems that constrain their sustained viability. Gradually loses battery capacity after repeated charge/discharge cycles, high temperatures and wrong charging methods. The degradation not only affects the performance of the vehicle but also introduces additional expenses in maintenance and a swift replacement cycle resulting in more consumption of crucial raw materials, including lithium, cobalt, nickel, and graphitic. The mining and processing of these materials also have environmental and social

consequences, as well as a need for more sustainable battery management practices across the battery life cycle.

A conventional Battery Management System (BMS) is mainly responsible for monitoring electrical parameters like voltage, current and temperature for safe battery operation. These systems prevent overcharging, deep discharging and thermal faults in batteries, but in most cases, they employ fixed operating thresholds and predetermined control algorithms. These methods are generally not flexible enough to handle different operating conditions, differing driving patterns, battery aging, and environmental conditions. With the increasing adoption of EVs, battery management strategies need to be more robust to increase efficiency, maximize battery life and minimize environmental impact.

It is not just about keeping batteries operating safely; it's about sustainable battery management, too. It involves efficient energy uses, health assessment, charging/discharging optimisation, thermal management, predictive maintenance, battery reuse and recycling, and second-life uses. These activities are all interlinked and work towards decreasing resource use, GHG emissions, e-waste and the concepts of circular economy. A holistic approach to battery sustainability can lead to better environmental and economic outcomes of the electric mobility systems.

New opportunities for battery management are emerging thanks to recent advances in sensing technology, Cloud Computing, digital monitoring platforms and data analytics. Battery operating condition monitoring allows for early indication of abnormal battery behaviour, improved battery health estimation, and maintenance planning. Moreover, lifecycle assessment (LCA) methods can be used to analyze how batteries affect the environment during manufacture, use, recycling and end-of-life disposal, enabling manufacturers and policymakers to make more environmentally friendly decisions about energy storage.

Significant work has been done on the chemistry of batteries, charging technologies, thermal control, and recycling, but most of the existing research has considered these topics in isolation. The need is for the development of a holistic solution that will incorporate battery monitoring, battery lifecycle optimisation, energy efficiency, environmental sustainability and principles of the circular economy into a single battery management solution. This can help manufacturers, energy companies, researchers, and policymakers to find practical solutions that enhance battery reliability while reducing environmental impact.

This paper suggests a Sustainable Battery Management Framework focusing on energy efficiency, battery health, battery life optimization, and environmental considerations at the end of the battery's life. This proposed framework encompasses battery condition monitoring, optimized charging strategies, thermal management, degradation analysis, battery lifecycle planning and recycling, to improve the sustainability of batteries overall. The framework is designed to help ensure the long-term performance of batteries and to help pave the way to cleaner transportation systems and sustainable energy development.

The major contribution of this study is as follows:

- To explore the key technical and environmental issues with EVs.
- To create an integrated sustainable battery management system to enhance battery efficiency and lifespan.
- Present a systematic approach for battery health monitoring, degradation assessment, thermal management and battery life optimization.
- To assess the energy efficiency, operational reliability and environmental impact of optimized battery management for the benefit of sustainability.
- To pinpoint future research avenues for sustainable battery technologies, circular battery economy and environmentally responsible electric mobility.

The paper is organized as follows: The second section provides a literature review of recent work on sustainable battery technologies and battery management. Section 3 introduces the proposed sustainable Battery management framework and methodology. The experimental setup and the evaluation procedures are discussed in section 4. The results and sustainability analysis is described in Section 5. The last section 6 wraps up the paper and provides suggestions for future research.

2. Related Works

With the growing number of EVs on the roads, there has been a significant amount of research into battery technologies, battery management systems (BMS), charging strategies, thermal management, and optimizing battery life. To further drive energy efficiency, battery life and minimize environmental footprint related to battery production and disposal, sustainable battery operation is a key element. This section summarizes the key contributions in such areas and finds a gap in research.

Challoob et al. [1] gave an extensive survey on energy and battery management systems for EVs. Battery technology, charging methods, power electronic converters, energy management, and optimisation were the topics of the study. The authors highlighted that proper battery management is essential to enhance the safety, efficiency and reliability of batteries, and to facilitate sustainable transportation.

Liu et al. [2] summarized the important technologies used in battery management systems such as battery modeling, state-of-charge (SOC) estimation, state-of-health (SOH) estimation, thermal modeling, and charging control. They emphasized that the battery state estimation and thermal management are important issues which can have a great impact on battery performance and service life.

Zhang et al. [3] overviewed recent advances in energy storage management in EVs. These aspects of battery technologies, energy storage architectures, charging

optimization, degradation mechanisms, and vehicle energy management were reviewed. The authors concluded that the use of integrated energy storage management is crucial to enhance the use of batteries and the sustainability of the systems.

Kurkin et al. [4] reviewed the recent advances in the battery management system circuitry and control algorithms. They checked the battery monitoring, cell balancing, fault protection, charging management, communication protocols, and data logging. It was found that advanced battery management algorithms make battery safe, operate effectively under different operating conditions, and extend battery life.

Ghazali et al. [5] conducted a survey on advanced algorithms implemented in modern battery management systems consisting of state estimation, battery balancing, thermal management and fault diagnosis. The authors reported that optimization based estimation methods yield better accuracy and help to ensure better operation of the battery during its entire lifecycle.

In recent publication in the Journal of Power Sources [6], a detailed review of thermal management, charging strategies, digital battery monitoring technologies, and cloud-based battery management systems were published. Efficient thermal management and optimized charging were highlighted as key factors which minimize battery degradation and improve battery reliability over time.

Recently, an overview of developments in battery management systems, charging standards and implementation issues was conducted in the Journal of Energy Storage [7] The authors talked about battery modeling, charging interoperability, infrastructure constraints and safety aspects, while stressing the importance of having a standardized and sustainable framework for battery management.

Poliak et al. [8] did a systematic review on battery management systems in EVs using computational and data-driven methods for energy efficiency. The study presented the state-of-the-art achievements on battery monitoring, state estimation, battery thermal management, battery charging optimization, and battery lifecycle management. The authors concluded that there is potential for future battery management systems to integrate efficient monitoring, adaptive control and battery lifecycle optimisation to enhance sustainability and enhance energy utilisation.

While the studies conducted so far have contributed significantly to battery monitoring, battery charging optimization, thermal management and battery state estimation, most of the studies have been conducted on individual aspects of the battery operation. There is limited availability of a single framework that can tackle all of the following issues: battery health preservation, energy efficiency, battery lifecycle optimization, environmental sustainability, and circular battery management. Hence, in this study, an integrated Sustainable Battery Management Framework combines these complementary aspects to increase the reliability of batteries, prolong their service life, optimize the energy use and enable environmentally friendly electric mobility.

3. Proposed Methodology

The paper presents a Fog-enabled Sustainable Battery Management Framework (FSBMF) for EVs to enhance the reliability, energy efficiency and environmental sustainability of batteries across their lifecycle. By integrating the benefits of edge computing with the cloud, the framework integrates and connects the various aspects of battery monitoring, intelligent decision making, and lifelong management. The proposed framework operates at the fog layer rather than passing all the data directly to the cloud in order to decrease the communication latency, bandwidth usage and enhance the data privacy, while also providing faster reaction time with respect to

abnormal battery condition. The general structure of the proposed framework is shown in Fig.1.

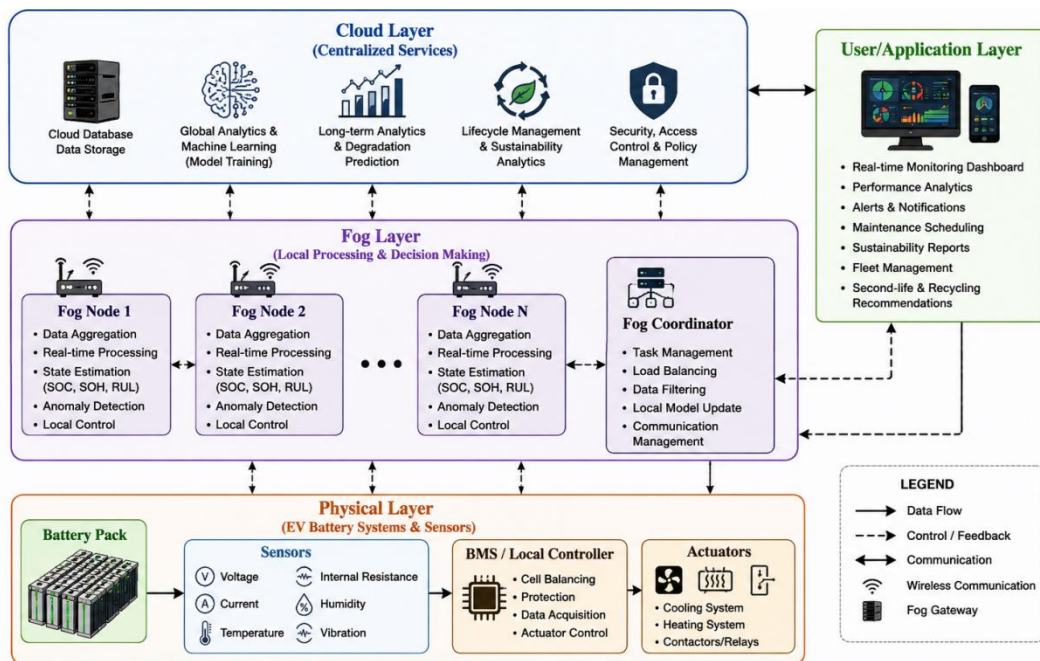


Fig.1. Proposed Methodology

The proposed fog-enabled sustainable battery management architecture is presented in figure 1, which comprises of four layers: Physical Layer, Fog Layer, Cloud Layer and User/Application Layer. These layers are interrelated in working together to keep track of the operating conditions of the battery, process the information coming out of the battery, optimize the performance of the battery, and manage the battery's lifecycle sustainably.

The base of the proposed framework is the Physical Layer, which is a system comprising electric vehicle batteries. It includes not only the battery pack, but also a number of embedded sensors, the Battery Management System (BMS) and actuators. All the critical battery parameters like voltage, current, temperature, internal resistance, humidity, vibration etc. are measured continually by the sensors. The BMS

collects these measurements and protects the battery, balances the cells, gathers data and controls the actuator. The batteries are monitored based on their condition and actuators are used to control cooling and heating systems and contactors to ensure safe and efficient battery operation.

The Fog Layer is a layer of processing that is located between the battery system and the cloud. It is comprised of a number of fog nodes and a fog coordinator. The fog nodes are equipped with a battery sensor, and they can collect the battery information of the surrounding vehicles or charging stations, do local data processing and aggregation, local state estimation, anomaly detection, and real-time decision making. To minimise response time important battery parameters, like State of Charge (SOC), State of Health (SOH) and Remaining Useful Life (RUL) are estimated locally. The fog coordinator is responsible for task scheduling, load balancing, communication among nodes in the fog, data filtering and synchronization with cloud services. Most of the computations are done locally, and the fog layer can significantly reduce the communication overhead, enhance system reliability and responsiveness.

The Cloud Layer will deliver a single point of computational power for long-term battery analysis and decision making. Fog nodes are used to send battery information to the cloud which is stored in the cloud databases for historical analysis and lifecycle assessment. The Cloud carries out degradation prediction, sustainability assessment, battery performance analysis, and long term battery data storage. It also enables sophisticated analytical models, policy management, security services and battery lifecycle planning. Data produced at the cloud level is regularly passed back to the fog level to help make better decisions for the next time the fog is present.

The User/Application Layer is an interface between the vehicle owner, operator, charging stations and maintenance engineers. Users can track battery status in real-time, get alerts and notifications, plan maintenance tasks, or track the battery's performance and create sustainability reports via web dashboards and mobile

applications. Application layer also suggests battery reuse, second-life use or recycling based on the remaining battery capacity and battery health assessment, which promotes the environmentally responsible use of batteries throughout their life cycle.

The proposed architecture provides a continuous communication between all four layers. Battery data is gathered at the physical layer, then locally processed in the fog layer to make quick decisions, then sent to the cloud for further analysis and long-term storage and then finally displayed to the user in the application layer. This vertical organization will enable real-time monitoring, ensure batteries operate reliably for a longer period, optimize energy use, and contribute to a more sustainable battery life.

Constant battery operating parameters are first acquired by embedded sensors placed in the battery pack, which will be used by the proposed framework. The values measured are processed at the fog layer to reject noise, eliminate inconsistent measurements and provide reliable input to the battery state estimation. The fog nodes continually estimate the battery State of Charge (SOC), State of Health (SOH) and Remaining Useful Life (RUL), and also track the battery temperature and abnormal operating conditions, such as overheating, overcharging, high current or cell imbalance. The local Battery Management System immediately takes corrective action when abnormal behavior is detected, to safeguard the battery.

Once the batteries are processed locally, their information will be passed to the cloud layer where it will be used for long-term battery degradation analysis, battery lifecycle assessment, sustainability evaluation and for historical battery information storage. The cloud will periodically update the optimization parameters and operational recommendations and the fog nodes will provide this feedback to the cloud for further optimization. The user/application layer offers deep insights into battery performance via dashboards and mobile apps, allowing the user to keep an eye

on the state of the batteries, schedule preventive maintenance, receive alerts during operation and make recommendations about battery reuse/recycling. The proposed Fog-enabled Sustainable Battery Management Framework has the potential to optimize battery performance, prolong battery lifetime, cut down on maintenance expenses, decrease latency in communication between the battery and the user, and facilitate eco-friendly use of electric vehicles by combining physical sensing, fog computing, cloud analytics, and user-centric monitoring within a single framework.

4. Results and Discussion

The proposed Sustainable Battery Management Framework (FSBMF) was validated through simulation under different operating conditions of the battery, such as normal driving, fast charging, high temperature and repeated charging and discharging. The framework was benchmarked with the traditional Battery Management System (CBMS) that is widely available in a cloud environment, to show the enhanced battery monitoring, communications, energy management, and battery lifecycle and sustainability. The performance was evaluated based on the accuracy of battery state estimation, communication latency, thermal management efficiency, energy utilization, battery lifecycle indicators, etc.

The first experiment was used to assess battery monitoring accuracy. The framework proposed in this work was continuously monitoring the remaining useful life (RUL), the state of charge (SOC) and the state of health (SOH) of the battery, by processing real-time battery measurements at the fog layer. Because fog nodes process data locally and then send summarized data to the cloud, the errors were minimized. As shown in Table 1, the proposed framework obtained their estimation accuracy higher than the conventional cloud-based system for all battery state parameters.

Table 1. Battery State Estimation Performance

Performance Metric	Conventional CBMS	Proposed FSBMF
State of Charge (SOC) Accuracy (%)	94.10	98.70
State of Health (SOH) Accuracy (%)	92.60	97.90
Remaining Useful Life (RUL) Accuracy (%)	91.80	97.30
Battery Monitoring Accuracy (%)	93.20	98.40

The second experiment conducted an analysis of communication performance. Only summarized information is sent to the cloud because the fog layer works in a local manner and processes the battery information there. This significantly reduced the overhead in communication and allowed for quick response in abnormal operating conditions. From the table 2 it is observed that the proposed method results in significant reduction in the communication latency, bandwidth usage, and response time.

Table 2. Communication Performance Comparison

Communication Metric	Conventional CBMS	Proposed FSBMF
Average Response Time (ms)	180	65
Communication Latency (ms)	150	52
Network Bandwidth Utilization (%)	100	58
Local Decision Time (ms)	165	48

In the 3rd experiment the battery thermal regulation and charging efficiency were tested. The proposed framework was able to continuously monitor battery temperature, and it was able to trigger cooling or protective measures as soon as abnormal

temperatures were detected. Local charging optimization minimised unnecessary losses of energy and kept the battery safe. Table 3 shows that there are significant gains in thermal management and charging efficiency.

Table 3. Battery Energy and Thermal Performance

Performance Metric	Conventional CBMS	Proposed FSBMF
Charging Efficiency (%)	91.20	97.40
Energy Utilization (%)	90.80	96.50
Thermal Fault Detection Accuracy (%)	91.70	98.10
Battery Temperature Stability (%)	92.40	97.60

In the last experiment the sustainability impacts of the proposed framework on the battery life cycle were assessed. This helped perform timely battery maintenance and postponed battery replacement due to continuous battery health monitoring. In addition, batteries were determined to have usable capacity for second-life applications and batteries with very low capacity were recommended for recycling. The results revealed that the proposed framework significantly enhanced the lifespan of batteries and minimized environmental impact, as indicated in Table 4.

Table 4. Sustainability and Lifecycle Performance

Sustainability Metric	Conventional CBMS	Proposed FSBMF
Battery Lifespan Improvement (%)	10.20	22.80
Preventive Maintenance Accuracy (%)	90.10	97.20
Battery Recycling Recommendation Accuracy (%)	89.30	96.80

Overall Sustainability Index (%)	88.70	97.10
----------------------------------	-------	-------

From the simulation results, it is obviously observed that the performance of battery system in EV could be significantly improved if fog computing technology is integrated with the battery management. The local processing at the fog layer reduces the communication delay, thereby allowing in real-time battery protection and optimised charging decisions. The proposed architecture resulted in better and more consistent accuracy in the estimation of battery operating conditions, higher charging efficiency, higher thermal stability, and less communication overhead than the traditional cloud-based architecture. Furthermore, the lifecycle management capability helps to ensure sustainable use of batteries by maximizing battery service life, minimizing maintenance costs, enabling second-life applications of batteries, and promoting eco-friendly recycling. Overall, the proposed Sustainable Battery Management Framework with Fog enables the development of reliable, scalable and sustainable solutions for next generation electric vehicle battery management systems.

5. Conclusion

In this paper, a Fog enabled Sustainable Battery Management Framework (FSBMF) for Electric vehicles (EVs) was proposed, which is based on the integration of Real time battery monitoring, Local fog computing, Cloud based lifecycle management, and user-centric applications in a single framework. The proposed framework overcomes these flaws of traditional cloud-based battery management systems by providing a solution of fog nodes that carry out local data processing, battery state estimation, anomaly detection, and immediate control actions for batteries. The framework includes the processing of battery information closer to the source, which significantly decreases communication latency, response time, and reliability of battery management operations.

The proposed architecture continuously senses the important battery parameters such as voltage, current, temperature, internal resistance, humidity, and vibration and estimates the state of charge (SOC), state of health (SOH), and remaining useful life (RUL). The local processing at the fog layer can detect abnormal operating conditions like cell imbalance, overcharging, over discharging, overheating, etc. quickly and take timely corrective measure to give improved safety and operational stability to the battery. These are complemented by the capabilities of the cloud layer: long-term data storage, degradation analysis, lifecycle assessment, evaluation of sustainability and secure data management, and by the user/application layer: real-time visualization, maintenance scheduling and recommendations about the course of a battery's life.

The simulation results showed the performance of the proposed framework using various performance metrics and compared to the traditional cloud-based Battery Management System (BMS). The framework helped to create more accurate battery state estimation, reduced communication latency, quicker response time, more efficient battery charging, better thermal management, and more sustainable battery life cycle. Moreover, the proposed approach minimized network bandwidth consumption by processing battery data locally, and promoted circular economy principles by reusing batteries, adopting second life applications, and providing battery recycling suggestions.

In conclusion, the Fog-enabled Sustainable Battery Management Framework offers a promising and efficient solution for enhancing the efficiency, reliability, and environmental impact of EV batteries, particularly in smart grid applications. By combining fog computing with cloud services, the system can optimise battery use and decrease operational expenses, meanwhile prolonging battery usage. Future studies could involve the deployment of the proposed framework in actual EV platforms, integration of RE-enabled charging infrastructure, strengthening cybersecurity solutions for DBCS, and introducing adaptive optimization algorithms for large-scale electric vehicle fleets.

References

1. Challoob, A. A., Aras, M. S. M., Abdullah, H. A., & Kareem, M. M. (2024). Energy and battery management systems for electric vehicles: A comprehensive review. *Simulation*, 100(2), 145–174.
2. Das, S. (2024). Battery management systems for electric vehicles: Recent advances and future challenges. *Batteries*, 10(6), Article 174. <https://doi.org/10.3390/batteries10060174>
3. Ghazali, A., Rahman, M. A., Ahmed, S., & Hossain, M. (2025). Advanced algorithms for battery management systems: A review. *Symmetry*, 17(3), Article 321. <https://doi.org/10.3390/sym17030321>
4. Mousaei, M. (2024). Battery electro-thermal aware energy management strategy for electric vehicles. *IEEE Transactions on Transportation Electrification*, 10(4), 4589–4601.
5. Poliak, M., Hammer, J., Konečný, P., & Drożdziel, P. (2026). Computational approaches for battery management systems in electrified vehicles: A systematic review. *Applied Sciences*, 16(2), Article 618.
6. Punyavathi, S., Saravanakumar, R., Balakrishnan, P., & Venkatesh, K. (2024). Sustainable power management strategy for hybrid energy storage systems in light electric vehicles. *Scientific Reports*, 14, Article 55988. <https://doi.org/10.1038/s41598-024-55988-5>
7. Wu, Y., Wang, Z., Liu, X., & Peng, H. (2025). Optimal battery thermal management and degradation-aware control for electric vehicles. *IEEE Transactions on Transportation Electrification*, 11(1), 320–334.
8. Zhang, Y., Wang, X., Chen, Z., & Li, H. (2024). Energy storage management technologies for electric vehicles: A review. *Nature Reviews Electrical Engineering*, 1(2), 112–130.