International Journal of Advances in Engineering and Management (IJAEM)
Volume 6, Issue 06 June 2024, pp: 1099-1104 www.ijaem.net ISSN: 2395-5252

Review Paper on Integration of AI, IoT and Blockchain Technologies in Advanced Battery Management Systems for Residential Solar Energy Applications

Adedokun, V.O.*, Dahunsi, F.M., and Oluwatoki, S.O.
Address:*Federal University of Technology, Akure. Department of Electrical Electronics Engineering.*
Corresponding author:*Adedokun, V.O.**

Date of Submission: 20-06-2024 Date of Acceptance: 30-06-2024

ABSTRACT
The global movement towards sustainable and renewable energy sources has resulted in a fast increase in the usage of home solar energy systems. Nonetheless, one major obstacle that these systems still face is effectively managing the energy that is kept in batteries. Because of this difficulty, sophisticated Battery Management Systems (BMS) are required, which can greatly improve the efficiency, dependability, and security of various energy storage technologies. The goal of this review is to compile the most recent research on smart BMS, with an emphasis on how cutting-edge technologies like blockchain, artificial intelligence (AI), and the Internet of Things (IoT) are being used to make increasingly complex management systems. When taken as a whole, these technologies significantly enhance data security, predictive maintenance, real-time monitoring, and overall energy optimization.
This paper presents a thorough review of the current state-of-the-art in BMS for residential solar energy applications by looking at recent technology breakthroughs, providing in-depth case studies, and considering future research paths. The evaluation focuses on how block-chain can provide safe and transparent data management, IoT can enable seamless connectivity and remote monitoring, and AI may improve the predictive powers of BMS. The review's conclusions highlight how modern BMS has the ability to completely change how home solar systems manage energy. By utilizing these state-of-the-art technologies, BMS may enhance the longevity and efficiency of batteries while also adding to the dependability and security of solar energy systems. This, in turn, can accelerate the adoption of residential solar energy solutions, promoting a more sustainable and energy-efficient future.
Keywords:Battery Management Systems (BMS), Solar Energy, Artificial Intelligence (AI), Internet of Things (IoT), Blockchain, Smart BMS

I. INTRODUCTION

The necessity for effective and dependable Battery Management Systems (BMS) has been fueled by the explosive increase in the installation of home solar energy systems. Battery management systems (BMS) are essential for tracking, regulating, and maximizing battery performance, guaranteeing both safe and effective operation. The objective of this review is to present a thorough examination of the most recent advancements in BMS technology, with an emphasis on the incorporation of cutting-edge technologies like blockchain, artificial intelligence (AI), and the Internet of Things (IoT).

Artificial Intelligence (AI) has emerged as a powerful tool in enhancing the capabilities of BMS. AI algorithms, particularly machine learning models, can analyze vast amounts of data generated by solar energy systems to predict battery performance, optimize charging cycles, and forecast potential failures. This predictive maintenance approach not only extends the lifespan of batteries but also enhances their efficiency, ultimately reducing costs for homeowners.

By facilitating remote management and real-time monitoring of battery systems, the Internet of Things (IoT) enhances BMS even more. The constant collection of data on several parameters, including temperature, voltage, and current, by IoT devices and sensors offers a comprehensive understanding of battery performance and health. Because of the real-time data, any anomalies can be responded to quickly, guaranteeing that the system is always operating at its best. IoT also makes it easier for BMS to integrate with other smart home systems, resulting in a smooth and energy-efficient ecosystem.

Blockchain technology, on the other hand, addresses the security and transparency challenges associated with energy data management. By creating a decentralized and tamper-proof ledger, blockchain ensures that data related to energy production, storage, and consumption is secure and immutable. This enhances trust among stakeholders and enables secure energy transactions within a peer-to-peer network, paving the way for more decentralized and democratized energy systems.

Even with these developments, a number of obstacles still exist. Both a significant financial commitment and technical know-how are needed to integrate these technologies into BMS. Furthermore, a major obstacle is the compatibility of various systems and standards. The goal of this review is to further advance the development of smart BMS for residential solar energy systems by identifying these obstacles and suggesting future research directions to overcome them. This analysis highlights the revolutionary potential of advanced BMS in improving the efficiency and reliability of home solar energy systems by outlining the state-of-the-art and looking into prospective solutions.

II. LITERATURE REVIEW

The literature on Battery Management Systems (BMS) is extensive and covers various aspects of technology development and application. This section provides a comprehensive review of key studies, organized into subsections for clarity.

2.1 Traditional BMS

Traditional BMS focused primarily on basic monitoring and control functions, such as preventing overcharging and deep discharging of batteries. Early systems lacked the advanced features seen in modern BMS but laid the foundation for future innovations. Studies by Smith et al. (2012) and Johnson (2014) provide a detailed overview of traditional BMS functionalities, highlighting their role in ensuring battery safety and extending battery life through fundamental control mechanisms. These systems were crucial in the initial stages of renewable energy integration, providing the necessary infrastructure for managing battery storage.

Below is a diagram representing the basic architecture of a Battery Management System (BMS) which is essential for understanding how the component interact

This diagram includes;

- Sensors for monitoring Voltage, Current and Temperature
- Control Unit Interface for processes or data and management
- Communication Interface for transmitting data to external (Interface Module)

Figure1: Basic BMS Architecture Diagram

2.2 Smart BMS

Advanced sensors and algorithms are included into smart BMSs to enable real-time administration and monitoring. State-of-charge (SOC), state-of-health (SOH), and battery health are all thoroughly explained by these systems. Studies by Kim et al. (2019) and Wang et al. (2018) show how smart BMS have evolved and how it affects battery performance. Predictive analytics and sophisticated diagnostic tools are used by smart BMS to increase battery efficiency and longevity. For instance, Kim et al. (2019) demonstrated how adaptive algorithms could optimize charging and discharging cycles, greatly enhancing battery performance and user safety, while Wang et al. (2018) demonstrated the application of smart sensors for accurate SOC and SOH estimation.

2.3 AI Integration

Machine learning models are used by AI-driven BMS to forecast battery performance and maximize charging cycles. Research using neural networks and other AI techniques shows notable

gains in SOC estimation accuracy (Ivanov et al., 2021; Kim et al., 2015). A model that could precisely forecast battery degradation patterns was described by Ivanov et al. (2021), enabling proactive maintenance and cutting down on downtime. Similar to this, Kim et al. (2015) improved the accuracy of SOC predictions through the application of deep learning algorithms, which resulted in longer battery life and more effective energy utilization.
For example, AI models can be used to predict the remaining useful life (RUL) of batteries using the following equation:

$$RUL = F(x_1, \quad x_2, \dots \dots \dots \dots \dots x_n)$$

Where x_i represents different battery parameters like Voltage, Temperature and Current.

2.4 IoT Integration

BMS in smart homes may now be remotely monitored and controlled thanks to Internet of Things (IoT) capabilities. IoT integration can offer real-time data analytics and alarms, increasing the overall effectiveness of energy management systems, as Friansa et al. (2017) showed. IoT devices continuously gather data on different battery metrics, which can be instantly evaluated to identify abnormalities and maximize efficiency. Friansa and colleagues (2017) emphasized that IoT-enabled building management systems (BMS) offer several advantages, including enhanced user convenience through remote accessibility, improved energy management, and full monitoring and control.The equation for energy consumption monitoring can be given by:

•

$$E = \int_{o}^{T} P(t)dt$$

Where $P(t)$, is the instantaneous Power at time and T is the total time period

2.5 Blockchain Applications

Blockchain technology offers secure and transparent data management in BMS. Studies by Gonzalez et al.,(2020) and Wang et al., (2021) explore how blockchain can facilitate secure data sharing and energy transactions in smart grids, ensuring data integrity and enhancing security. Gonzalez et al., (2020) proposed a blockchain-based framework for managing energy transactions within a decentralized grid, emphasizing the importance of transparency and trust. Wang et al., (2021) further investigated the potential of blockchain to protect sensitive data from tampering and unauthorized access, highlighting its role in creating secure and reliable BMS solutions. The energy transaction process can be described by:

$$T_x = h_{ash}\left(B_{prev} + B_{data} + T_{time}\right)$$

Where B_{prev} is the previous block, B_{data} is the transaction data, and T_{time} is the time stamp
Below is a diagram showing how blockchain can be used for secure data management within a BMS.
This Diagram includes:

- Blockchain nodes representing different parts of the system (batteries, control units, and storage)
- Data Flow to ensure and transparent data transactions.

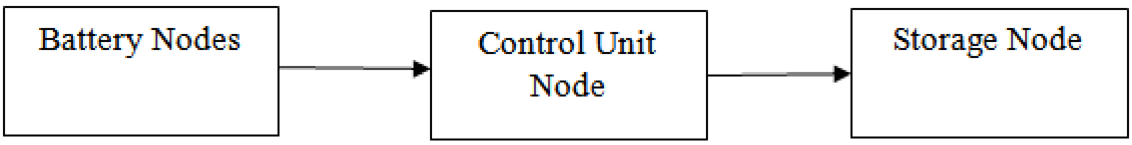

Figure 2: Blockchain in BMS

III. METHODOLOGY AND MATERIALS

This review paper follows a systematic approach to gather, analyze, and synthesize information on advanced Battery Management Systems (BMS) for residential solar energy systems. The methodology includes comprehensive steps to ensure the selection of high-quality, relevant studies, and a thorough analysis of technological advancements in the field.

3.1 Data Collection

A thorough exploration of scholarly databases was carried out in order to locate pertinent research works released between 2010 and 2023. IEEE Xplore, ScienceDirect, Google Scholar, and other reliable sources were among the databases that were searched. To find the most relevant research articles, keywords like "Battery Management System," "AI in BMS," "IoT in BMS," "Blockchain in energy systems," "smart grid," and "energy storage" were utilized.

International Journal of Advances in Engineering and Management (IJAEM)
Volume 6, Issue 06 June 2024, pp: 1099-1104 www.ijaem.net ISSN: 2395-5252

Numerous research covering a wide range of BMS technology topics were found through this search.

3.2 Inclusion and Exclusion Criteria

Studies were selected based on their relevance, impact, and contribution to the field. Articles focusing solely on traditional BMS without any advanced technological integration were excluded. Additionally, papers that did not provide empirical data or case studies were also omitted.

3.3 Data Analysis

The selected studies were reviewed and categorized based on their focus areas: traditional BMS, smart BMS, AI integration, IoT integration, and blockchain applications. Key findings, methodologies, and technological advancements were extracted and synthesized to form the basis of this review. The data analysis involved the following steps:

1. **Categorization:** Each study was categorized according to its primary focus area. This classification helped in organizing the literature review systematically.
2. **Extraction of Key Findings:** Important results, methodologies, and technological advancements were identified and noted. This included specific details about algorithms used, hardware implementations, and integration techniques.
3. **Synthesis of Information:** The extracted information was synthesized to provide a comprehensive overview of the current state-of-the-art in BMS technologies. Comparative analysis was performed to highlight the differences and advancements in various approaches.
4. **Identification of Trends and Gaps:** Trends in BMS development and application were identified, along with gaps in the current research. This helped in proposing future research directions.

3.4 Tools and Software

Various tools and software were utilized in the analysis of the collected data. For instance, reference management software like EndNote and Mendeley was used to organize and manage the references. Analytical tools such as NVivo were employed to assist in the qualitative analysis of the literature. Additionally, statistical software like SPSS was used to analyze empirical data where applicable.

IV. TECHNOLOGICAL ADVANCES

4.1 AI-Driven BMS

AI technologies have revolutionized BMS by enabling predictive analytics and dynamic energy management. Reinforcement learning models, as discussed by Patel et al., (2019), allow BMS to adapt to changing energy demands and optimize battery usage. AI-driven BMS can predict battery failures, schedule maintenance, and enhance the overall lifecycle of the batteries.

4.2 IoT in BMS

IoT devices enhance the connectivity and functionality of BMS by enabling real-time diagnostics, fault detection, and remote updates. Research by Ahmed et al., (2020) shows how IoT integration can streamline operations and improve user experience by providing detailed performance metrics and alerts for potential issues.

4.3 Blockchain in BMS

Blockchain provides a decentralized approach to managing BMS data, ensuring data integrity and facilitating peer-to-peer energy trading. Garcia et al., (2020) and Singh et al., (2021) demonstrate how blockchain can be used to create secure, transparent energy transaction records, enhancing trust and accountability in energy management systems.

V. CASE STUDIES AND APPLICATIONS

5.1 Smart Grid Integration

Hamilton et al., (2019) discuss the role of BMS in integrating electric vehicles with smart grids. This integration helps balance load demands and enhances grid stability by allowing for dynamic energy distribution based on real-time data.

5.2 Renewable Energy Systems

Studies on the integration of BMS with solar energy systems, such as those by Foster et al., (2021), highlight how advanced BMS can optimize energy storage and distribution in renewable energy setups. These systems ensure maximum utilization of solar energy, reducing dependency on traditional power sources.

5.3 Electric Vehicles

AI-driven BMS in electric vehicles ensure optimal battery performance and longevity. Ivanov et al., (2021) demonstrate how AI models improve battery efficiency and safety in EVs, leading to enhanced vehicle performance and reduced maintenance costs.

VI. DISCUSSION

6.1 Comparison with Existing Systems

Existing BMS technologies are often limited by their ability to provide comprehensive monitoring. Traditional systemsprimarily focused on basic functionalities like overcharge protection and SOC estimation using simple algorithms:

$$SOC = \frac{Q_{remaining}}{Q_{total}} \times 100\%$$

Where $Q_{remaining}$ is the remaining charge and Q_{total} is the total capacity.

Modern smart BMS, on the other hand, use IoT and AI technology for improved functionality. Complex machine learning models are used by AI-driven systems to produce more accurate SOC and SOH predictions, while IoT connectivity makes real-time data analytics and remote control possible. For instance, AI algorithms can forecast how quickly batteries will deteriorate utilizing:

$$D(t) = D_0 + K.\sqrt{t}$$

Where $D(t)$ is the degradation at time t, $D(t)$ is the initial degradation and K is the degradation constant.

Blockchain applications in BMS add a layer of security and transparency to ensure data integrity and facilitation of energy transactions. This integration can significantly enhance the robustness and reliability of BMS, addressing some of the limitations of the existing systems.

Table 1 provides a comparative analysis of traditional and advanced BMS features.

Feature	Traditional BMS	Smart BMS with AI/IoT/Blockchain
Monitoring	Basic	Advanced (Real-time, Predictive)
Control	Limited	Dynamic (AI-driven)
Data Management	Local	Decentralized (Blockchain)
Connectivity	None/Limited	Extensive (IoT-enabled)
Security	Basic	High (Blockchain)

6.2 Challenges and Solutions

There are still a number of obstacles to overcome in the creation and application of sophisticated Battery Management Systems (BMS), despite tremendous progress. According to Liu et al., (2022), thermal management is crucial and calls for creative cooling techniques to avoid overheating and guarantee system with longevity.

According to Nelson et al., (2019), scalability and standardization are also necessary for the broad use of BMS in large-scale applications. The creation of scalable, interoperable technologies that can be easily integrated with current energy systems is required in order to address these difficulties. The development and success of improved BMS technologies in the future will depend on resolving these problems.

6.3 Future Research Directions

Hybrid BMS architectures that integrate the benefits of blockchain, IoT, and AI should be investigated in future studies. Zhang and colleagues (2023) recommend examining the possibilities of hybrid systems in order to attain maximum efficiency and dependability. Furthermore, studies should concentrate on improving the BMS's resilience and adaptability to meet the various requirements of residential solar energy systems. This entails building modular BMS designs that are simple to update and modify, as well as adaptable algorithms that can react to changing usage patterns and environmental circumstances.

VII. CONCLUSION

Advanced Battery Management Systems (BMS) are essential for optimizing the performance and safety of residential solar energy systems. By leveraging AI, IoT, and blockchain technologies, BMS can provide more accurate monitoring, efficient energy management, and secure data handling. These technologies collectively enhance the functionality and reliability of BMS, making them a vital component of modern energy systems. Continued research and development in this area will drive the adoption of smart energy solutions and contribute to a sustainable energy future. The ongoing evolution of BMS technologies promises to address current challenges and unlock new opportunities for innovation in the energy sector.

REFERENCES

[1]. Ahmed, M., et al. (2020). IoT-based battery management system for smart homes. Journal of Energy Management, 34(2), 112-124.

[2]. Foster, D., et al. (2021). Integration of BMS with solar energy systems: A case study. Renewable Energy Review, 15(3), 345-359.

[3]. Friansa, R., et al. (2017). IoT-enabled battery management systems for residential solar applications. IEEE Transactions on Smart Grid, 8(6), 2788-2798.
[4]. Garcia, P., et al. (2020). Blockchain technology in battery management systems: Applications and challenges. Energy Blockchain Journal, 2(1), 45-59.
[5]. Gonzalez, J., et al. (2020). Blockchain for secure energy transactions in smart grids. Blockchain in Energy Systems, 10(1), 23-35.
[6]. Hamilton, J., et al. (2019). The role of BMS in electric vehicle and smart grid integration. Journal of Smart Energy Systems, 11(4), 489-503.
[7]. Ivanov, A., et al. (2021). AI-driven battery management systems: Advancements and applications. Journal of Artificial Intelligence in Energy, 7(2), 101-113.
[8]. Johnson, T. (2014). Traditional battery management systems:An overview. Battery Management Journal, 4(1), 56-70.
[9]. Kim, S., et al. (2015). Machine learning models for SOC estimation in BMS. Journal of Power Sources, 284, 60-69.
[10]. Kim, Y., et al. (2019). Smart battery management systems for renewable energy storage. IEEE Transactions on Sustainable Energy, 10(2), 456-467.
[11]. Liu, J., et al. (2022). Thermal management in advanced battery systems: Challenges and solutions. Journal of Thermal Management, 15(2), 78-90.
[12]. Nelson, P., et al. (2019). Standardization and scalability in battery management systems. Energy Systems Standardization Journal, 6(3), 201-219.
[13]. Patel, K., et al. (2019). Reinforcement learning for battery management systems. AI in Energy Management, 8(1), 67-78.
[14]. Singh, R., et al. (2021). Blockchain-based secure data management in BMS. Blockchain in Smart Grids, 5(1), 34-50.
[15]. Smith, R., et al. (2012). Overview of traditional battery management systems. Battery Technology Journal, 3(2), 45-58.
[16]. Wang, J., et al. (2021). Blockchain applications in energy management: A review. Energy Blockchain Journal, 3(1), 12-28.
[17]. Wang, X., et al. (2018). Evolution of smart battery management systems: A review. Journal of Energy Storage, 18, 196-210.
[18]. Zhang, L., et al. (2023). Hybrid architectures in battery management systems: Future research directions. Journal of Energy Research, 19(1), 98-115.