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Review Article

A Blockchain and IoT-Based Sustainable Battery Monitoring Framework for Smart Electric Drive Systems

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A B S T R A C T

This paper outlines a theoretical framework for a sustainable, intelligent, and secure system for monitoring batteries by leveraging the combined strengths of blockchain and Internet of Things (IoT) technologies. As electric vehicles (EVs) gain popularity, the need for reliable, transparent, and tamper-resistant battery management solutions is increasing. Conventional Battery Management Systems (BMS) depend on centralised data storage and lack predictive functionalities, which renders them susceptible to manipulation and inefficiencies. The proposed architecture introduces a decentralised model that envisions real-time collection of sensor data, synchronised processing of events, and immutable logging of data via blockchain. Additionally, the model integrates theoretical machine learning algorithms aimed at forecasting battery state-of-health and detecting anomalies. The framework operates through a multi-layered structure that includes data acquisition, synchronisation, blockchain encoding, predictive analytics, and user interaction—each component defined as a functional abstraction to guarantee adaptability and compatibility across platforms. The model anticipates various applications in fleet management, energy trading, vehicles connected to the grid, and warranty enforcement, fostering a more transparent and accountable ecosystem for EVs. By excluding hardware specifications and concentrating purely on theoretical aspects, this paper establishes a foundation for academic exploration and future technological implementation.

Keywords: Blockchain in Battery Management, IoT-Based Monitoring Systems, Smart Electric Drive Systems, Battery Health Prediction, Decentralized Data Integrity

Introduction

The increasing use of electric vehicles (EVs) in multi-stakeholder ecosystems such as fleet operations, battery leasing, and decentralised energy grids presents complex challenges in battery monitoring, health prediction, and transparency.[1,2] Traditional battery management systems (BMS) rely on centralised architectures and rigid firmware, which lack real-time adaptability, traceable diagnostics, and cryptographic security, resulting in inefficiencies, cyber vulnerabilities, and limited predictive maintenance.[3,4]

They are unable to meet emerging smart city needs such as energy sharing, dynamic pricing, and multi-node coordination.[5] This paper proposes a modular BlockchainIoT architecture: the IoT layer enables multi-point sensing of temperature, voltage, current, and charge-discharge cycles for anomaly detection[6,7] while Blockchain ensures integrity and secure EV-OEM utility interactions through cryptographic immutability, decentralised consensus, and role-based smart contracts[2,8,9] allowing for scalable, energy-efficient, and digitally responsible BMS models.[10,11]

Literature Review

Recent research has investigated various Battery Management System (BMS) solutions that use Internet of Things (IoT) technology. Wireless sensor networks allow for real-time measurement of battery voltage, temperature, and state of charge for continuous monitoring.[1] However, traditional IoT-based systems frequently rely on centralised cloud infrastructures, which pose risks to data availability, privacy, and integrity in mission-critical domains such as electric mobility.[2] Blockchain addresses these limitations by using decentralised, tamper-proof recordkeeping and smart contracts to enforce rules like overvoltage or thermal thresholds.[3] In trustless ecosystems, Christidis and Devetsikiotis[4] demonstrated secure communication between IoT devices. This paradigm, which is gaining traction in industries such as energy trading and supply chain management where traceability is critical[5,6] has significant potential for EV battery monitoring, though its integration into real-time embedded systems is still largely unexplored.

A significant gap in previous research is the absence of a cohesive, modular architecture that combines distributed ledgers, machine learning analytics, and real-time sensing. Existing approaches frequently treat IoT and blockchain separately, without orchestration layers for temporal synchronisation, privacy-preserving access, and predictive diagnostics. Many also lack the scalability needed for smart microgrids, battery leasing, and vehicle-to-grid (V2G) systems.[7,8] This study proposes a multi-layered architecture that combines blockchain, IoT, and AI-powered analytics to provide secure, transparent, and adaptive battery monitoring for sustainable electric drive systems.

The Figure: 1 is a timeline diagram illustrating the evolution of IoT- and blockchain-based technologies in battery monitoring and energy trading from 2014 to 2024.

- **2014 – IoT-Based BMS:** Introduction of Internet of Things (IoT) in battery monitoring systems. 2018 –
- **Blockchain in Energy Trading:** Peer-to-peer (P2P) energy trading begins using blockchain.
- **Remote BMS Access:** Secure remote access to battery management systems.
- **2018 (later) – Integrated IoT + Blockchain:** Merging IoT data acquisition with blockchain security for energy systems.
- **2020 – IoT + Blockchain Framework:** Establishment of a combined framework enabling decentralised storage and advanced P2P energy transactions.
- **2024:** Ongoing integration and expansion of P2P trading and decentralised storage architecture.

In short, it's a visual historical progression showing how the proposed integrated IoT-blockchain framework builds upon past innovations.

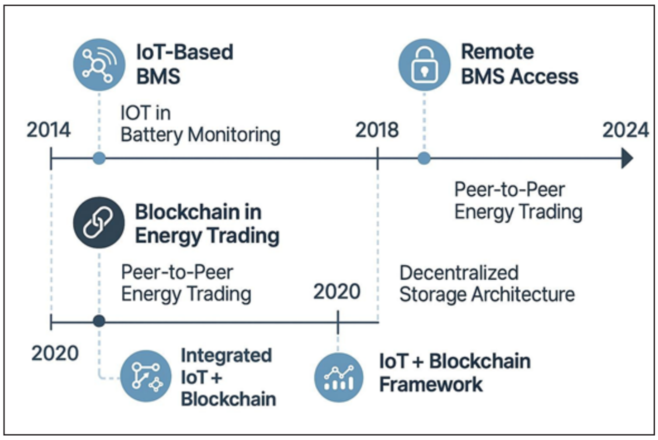

Figure 1.Timeline diagram of this framework

Theoretical Framework

This study proposes a five-layer modular framework that combines blockchain recordkeeping, IoT sensing, and AI diagnostics to provide dependable, scalable EV battery monitoring. Each layer abstracts key functions to ensure cross-platform interoperability and integration with smart transportation systems. The adaptable design enables improvements in consensus, analytics, and sensing without disrupting the overall architecture.

Acquisition Layer

This layer entails the symbolic real-time sensing of vital battery metrics such as state-of-charge (SOC), voltage, temperature, and current. In this theoretical concept, IoT sensors are virtualised and record data at predetermined intervals or at particular occurrences, such as rapid charging or overheating. By removing hardware-specific dependencies, the abstraction enables the framework to concentrate on information flow and system reaction instead of sensor design. It lays the foundation for diagnostic intelligence and is consistent with the methods Li and Xie[9] provide for smart settings.

Synchronization Layer

This layer maintains the temporal integrity of data since several sensor nodes function asynchronously. It reorganises and validates data streams for precise sequencing using error-correcting codes, redundancy checks, and timestamp normalisation. In situations where millisecond-level accuracy

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may be crucial, such as thermal runaway or short-circuit alarms, this helps remove uncertainty in event correlation. Decentralised blockchain-based logging requires this kind of predictable ordering.[3]

Blockchain Layer

This is where data immutability is fundamental. Each data packet is kept in a block, including metadata such as location, time, and sensor ID, after being cryptographically hashed (for example, using SHA-256). Validation logic (e.g., "if SOC < 20% and temp > 45°C, then log warning") is executed using smart contracts.[2,5] As a tamper-proof record of battery activity over time, these blocks create a verifiable chain. Additionally, it facilitates multi-party auditability, which allows OEMs or regulators to examine logs without having direct access to sensors.[6]

Analytics Layer

This layer abstracts machine learning (ML) models such as Convolutional Neural Networks (CNNs) for pattern recognition and Long Short-Term Memory (LSTM) networks for time series forecasting. They receive theoretical training using structured datasets that depict the behaviours of batteries. The layer classifies flaws such as temperature deviation or cell imbalance, forecasts state-of-health (SOH), and flags abnormalities. Using federated models preserves data privacy while enabling cross-vehicle learning.[4,7,13]

User Interface Layer

This uppermost layer is role-based and offers various stakeholders customised information. For instance, manufacturers get access to lifetime heatmaps, and fleet managers receive information on deterioration trends. In order to maintain privacy and usability, dashboards are designed to abstract data complexity without disclosing raw records.[12] Fine-grained data access is possible through the use of pseudonymous blockchain keys to provide authorisation for interactions.

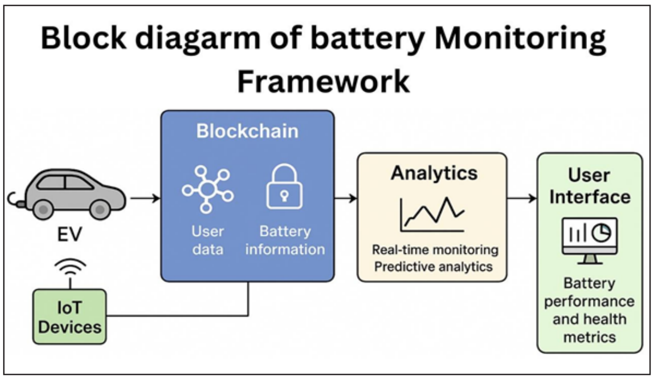

Figure 2.Block Diagram of Battery Monitoring Framework

Figure 2 represents a data flow architecture for an EV battery monitoring system integrating IoT, blockchain, and analytics:

- EV (Electric Vehicle) → The source of real-time operational and battery data.
- IoT Devices → Collect parameters such as voltage, temperature, and state-of-charge from the EV's battery system and transmit them wirelessly.
- Blockchain Module → Securely stores user data and battery information in a tamper-proof, decentralised ledger for transparency and trust.
- Analytics Module → Performs real-time monitoring and predictive analytics to assess battery performance, detect anomalies, and forecast health status.
- User Interface → Displays battery performance and health metrics to stakeholders via dashboards.

In short, it's a conceptual workflow showing how IoT-based battery data is securely logged on blockchain, analysed, and presented to end users.

Methodology

The suggested modular platform simulates, organises, secures, and analyses electric car battery events without relying on hardware prototypes.It combines IoT-based sensing, blockchain-based event verification, and AI diagnoses trained on synthetic data.This layered method ensures that all stages of battery operation—from acquisition to visualisation—can be safely recorded, synchronised, and interpreted, allowing for scalable, privacy-preserving, and decentralised battery management models.

Virtual Sensor Data Simulation

Synthetic datasets are used to model various battery characteristics such as quick charging, deep draining, overheating, and load balancing.Each simulated event includes time-series voltage, current, and temperature data, which mimics genuine embedded sensors.These symbolic data streams retain the asynchronous sampling properties present in IoT-based BMS designs,[4,9] and[12], enabling system testing and diagnostic modelling without physical hardware dependencies.

Structured Event Representation

Every sensor measurement is converted into a standard schema consisting of:

- Parameter Category (e.g., SOC, Temp)
- Event Label (e.g., thermal breach)
- Timestamp
- Deviation Score
- Node Identity (pseudonymized)

This abstraction corresponds with structured event modelling for machine intelligence systems in BMS.[4,7]

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Blockchain Encoding with Smart Contracts

Sensor events are hashed using SHA-256 and archived in Merkle Tree-based block formats. The blockchain layer documents immutable overviews of performance data. Smart contracts trigger logical responses such as:

- If Voltage < 2.5V → Flag undervoltage alert
- If SOC < 20% + High Temp → Log Emergency Discharge Condition

This supports previous implementations of smart contracts in IoT security[3,6] and energy networks.[5,8]

Machine Learning Integration

The Analytics Layer uses LSTM to monitor temporal degradation and CNNs to identify anomaly patterns from charge/discharge cycles. Federated learning is suggested for future integration—enabling distributed EV fleets or battery operators to collaboratively function on models while maintaining privacy.[10,13] Algorithms focus on early identification of problems like lithium plating, capacity fade, and rapid thermal increase.[4,11]

Role-Based Access and Visualization Protocols

The results from the analytics pipeline—insights, logs, alerts—are made available to various users through dashboards regulated by cryptographic keys. OEMs, regulatory agencies, and operators receive selective access, enforced via a permissioned blockchain layer as mentioned in[2,6] and supported by user hierarchy models from.[14]

Analysis And Implications

The combination of blockchain and IoT in battery monitoring significantly transforms the methods of data collection, interpretation, and trustworthiness within electric vehicle (EV) systems. Conventional Battery Management Systems (BMS) react only after problems arise, depending on centralised storage that can be manipulated and lacks thorough traceability. Conversely, this new approach presents a proactive and verifiable diagnostic framework, allowing for immediate responses, predictive malfunction identification, and historical verification through unalterable blockchain records.[3,5]

By implementing deep learning algorithms (such as LSTM for state of health prediction and CNN for identifying anomalies) on symbolically synchronised IoT datasets, the system shifts from basic monitoring to AI-driven adaptive control. For instance, a sudden drop in voltage along with an increase in temperature may automatically activate smart contracts to initiate safe-mode procedures, notify stakeholders, and securely record events—enabling prompt action and data-supported troubleshooting.[4,7]

From a security and compliance standpoint, blockchain guarantees unalterable records and access controls. This is crucial for scenarios like warranty verification, carbon credit tracking, and regulatory assessments. Incidents like thermal breaches or excessive discharges are permanently documented and timestamped—helping to resolve disputes and instilling confidence in second-hand EV markets.[2,5,6]

Moreover, this framework aids in optimising costs and maintaining service continuity in fleet management or smart grid integration. Operators can plan preventive maintenance based on real usage and degradation trends, which minimises unexpected failures and reduces downtime.[8,9] As all components communicate via a decentralised framework, the system can efficiently scale across numerous vehicles or battery packs, ensuring overall integrity and accountability at the platform level.

Use Cases

The proposed Blockchain-IoT-AI architecture provides a unified, modular solution for overcoming chronic restrictions in Battery Management Systems (BMS), including trust, scalability, and predictive diagnostics. Real-time IoT telemetry collects SOC, voltage, and thermal data, while blockchain enables tamper-proof storage and enforces operating thresholds using smart contracts.[3,5] AI-driven analytics, such as LSTM forecasting and CNN anomaly detection[4,7], allow for preventive maintenance, performance improvement, and accurate SOH prediction. This integration benefits EV fleets by reducing downtime, validating warranties, and optimising asset use, whereas in smart grids it enables verified SOH-based load balancing[5,8].Immutable usage records for Battery-as-a-Service (BaaS) improve leasing models by guaranteeing transparent value evaluation.[8,11]

Aside from operational benefits, the system provides cryptographic verification for ESG compliance, automated emissions reporting, and regulatory audits.[6,13] Blockchain-coordinated energy distribution promotes ideal units while flagging inefficient ones for recycling, hence improving sustainability. In peer-to-peer trading, authenticated charge/discharge histories enable tokenised renewable energy transactions with verifiable provenance.[10,14] By combining interoperability, privacy-preserving analytics, and distributed governance, this architecture creates a scalable, resilient framework that can be applied to EV mobility, microgrids, and decentralised energy markets, delivering transparent operations, adaptive optimisation, and long-term sustainability in a rapidly changing clean energy ecosystem.

Future Scope

The use of blockchain and IoT in battery monitoring not only addresses transparency, security, and diagnostics issues but also allows for developments beyond current

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mobility and energy models. Future initiatives include Federated Learning (FL), in which EV battery controllers and smart chargers train models locally on consumption, health, and the environment while only sharing aggregated metrics.[7,10] This improves privacy, lowers network strain, and ensures GDPR and DPDP compliance.[13] Lightweight consensus protocols such as Proof-of-Authority (PoA) and Directed Acyclic Graphs (DAGs) will enable millisecond-level validation for safety-critical use cases such as self-driving cars and drone fleets[3,12] while avoiding the latency and resource requirements of Proof-of-Work.

Battery digital twins are another breakthrough—real-time virtual duplicates linked with operational data that save certified lifespan records on blockchain for warranty, resale, and carbon credit markets.[11,14] This architecture may dynamically route energy in intelligent microgrids, favouring healthy units for vital loads and flagging degraded cells for recycling.[5,8] Future-proofing may include quantum-resistant cryptography to defend against post-quantum threats, as well as preserving critical energy data in defence, transportation, and grid systems.[6,15] These advancements establish the framework as a critical enabler of secure, adaptive, and sustainable battery ecosystems.

Conclusion

The transition to electric transportation and smart energy networks necessitates a paradigm shift in battery monitoring and management. This paper presents a multi-layered theoretical framework that combines blockchain, IoT, and sophisticated analytics to promote transparency, reliability, and sustainability in intelligent electric drive systems. Unlike traditional BMS approaches, which rely on centralised storage and reactive diagnostics, the proposed architecture provides decentralised, tamperproof, and predictive oversight, increasing technical efficiency while promoting operational trust and regulatory compliance. Its modular design, which includes acquisition, synchronisation, blockchain encoding, analytics, and user interfaces, provides adaptation across several platforms and stakeholders, ranging from OEMs to regulators, while maintaining interoperability and data integrity.

The platform allows for preventive diagnostics by incorporating machine learning models such as LSTMs and CNNs, while blockchain smart contracts enforce operational norms and verifiable event logging.It envisions future capabilities such as federated learning, digital twins, safe energy tokenisation, and adaptive microgrid coordination. Potential applications include fleet optimisation, smart grids, battery-as-a-service models, and sustainability audits. As electric vehicles, IoT, and blockchain technologies advance, such designs will play critical roles in establishing safe, adaptive, and egalitarian energy ecosystems that support global decarbonisation and the digital energy revolution.

Declaration Of Interest

The author states that there are no conflicts of interest related to the publication of this manuscript. The research was carried out independently, without any commercial or financial ties that could be viewed as a potential conflict of interest.

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