J. Electrical Systems 21-1s (2025): 148-157

[1] Yogi Bhadreshkumar Joshi
[2] Satyam Kumar Singh

Decentralizing Energy Storage Monitoring: A Blockchain-Enabled Solution for Enhanced Transparency and Security

Abstract: Energy storage systems (ESS) are becoming more and more necessary to maintain grid stability and supply-demand balance as a result of the quick adoption of renewable energy sources. Centralized monitoring systems for ESS, however, present a number of difficulties, such as the possibility of data manipulation, a lack of transparency, security flaws, and inefficiencies in energy exchanges. In order to improve operational efficiency, security, and transparency, this study suggests a decentralized energy storage monitoring system that makes use of blockchain technology. The suggested method makes use of smart contracts and blockchain's immutable ledger to build an energy storage monitoring system that is impenetrable and untrustworthy. The solution allows for safe, automatic energy data collection and verification by combining blockchain technology with edge computing and real-time Internet of Things (IoT) sensors. Autonomous energy transactions are made possible by smart contracts, which also provide equitable pricing procedures and lessen dependency on middlemen. By removing single points of failure, the decentralized design also improves cybersecurity by reducing threats like data breaches, cyberattacks, and unauthorized access. Furthermore, a consensus mechanism like Proof of Authority (PoA) or Proof of Stake (PoS) is introduced by the blockchain-based system to confirm transactions effectively without the high computational costs of Proof of Work (PoW). This preserves scalability while guaranteeing low-latency, real-time data validation. Additionally, the use of tokenized incentives motivates energy producers and consumers to actively engage in peer-to-peer energy trading and grid balancing.

Keywords: Peer-to-peer energy trading, blockchain technology, smart contracts, decentralized energy storage, transparency and security, energy storage monitoring, and professor to shake

1. INTRODUCTION

Because blockchain technology has the potential to improve energy management's efficiency, security, and transparency, its integration into the energy industry has drawn a lot of attention. Decentralized energy trade, safe data management, and real-time energy storage system monitoring are made possible by blockchain, which helps to accomplish the Sustainable Development Goals (1). Blockchain ensures safe transactions and enables effective peer-to-peer (P2P) energy trading by utilizing smart contracts (1,2). In energy management systems, the technology is also essential for cybersecurity, reducing the dangers of data breaches and illegal access (3,4). Additionally, by optimizing energy use and encouraging the adoption of renewable energy, blockchain's decentralized nature promotes sustainability and lowers carbon footprints (5,6,7). Notwithstanding its benefits, scaling issues, regulatory limitations, and

---

joshiyogi97@gmail.com
satyam7833@gmail.com

integration difficulties are some of the obstacles to blockchain implementation in the energy industry (8,9). For broad adoption, these obstacles must be removed by legislative measures and technical developments (10,11). Furthermore, blockchain technology has applications outside of the energy sector, providing creative solutions for a range of sectors, such as healthcare and banking (12,13). Future advances will continue to focus on blockchain's effects on economic, social, and environmental sustainability as studies into its function in decentralized energy management continue (14).

1.1. The Need for Energy Storage Monitoring

With the growing adoption of renewable energy sources such as solar and wind power, the reliance on energy storage has increased significantly. Energy storage solutions, including lithium-ion batteries, pumped hydro storage, and hydrogen fuel cells, are critical for stabilizing the power grid and ensuring continuous electricity supply. However, effective monitoring of energy storage is essential for:

- Ensuring real-time tracking of energy production, consumption, and storage.
- Preventing unauthorized data manipulation or cyberattacks.
- Optimizing energy efficiency through predictive analytics and anomaly detection.

Enabling fair and transparent energy transactions in distributed energy markets.

Traditional energy storage monitoring systems rely on centralized servers and third-party control, leading to vulnerabilities such as single points of failure, data inconsistencies, and high operational costs.

1.2. Challenge in Centralized Energy Storage Monitoring

Despite advancements in energy storage technologies, existing monitoring frameworks face several limitations due to their centralized nature:

- **Lack of Transparency:** Centralized systems are managed by a single authority, raising concerns about data integrity, manipulation, and lack of trust among stakeholders.
- **Security Vulnerabilities:** A single point of failure in centralized databases makes them susceptible to cyberattacks, data breaches, and unauthorized access.
- **Inefficiencies in Energy Transactions:** Intermediaries and centralized control mechanisms often introduce delays, inefficiencies, and high transaction costs in energy trading.
- **Data Integrity and Trust Issues:** The reliance on third-party validation limits the ability to independently verify the accuracy and reliability of stored energy data.

1.3. Blockchain as a Solution for Decentralized Energy Storage Monitoring

Blockchain technology offers a decentralized and secure alternative to traditional energy monitoring systems. The key features of blockchain that make it suitable for energy storage applications include:

- **Immutability:** Data recorded on the blockchain cannot be altered or deleted, ensuring transparency and accountability.
- **Decentralization:** Eliminates the need for central authorities, reducing the risk of data manipulation and cyberattacks.

- **Smart Contracts:** Self-executing contracts automate energy transactions, enabling peer-to-peer (P2P) energy trading without intermediaries.
- **Consensus Mechanisms:** Proof of Authority (PoA) and Proof of Stake (PoS) ensure secure and efficient transaction validation while minimizing energy consumption.

2. LITERATURE REVIEW

In the energy industry, blockchain technology has become a game-changer, especially when it comes to improving decentralized energy storage monitoring's efficiency, security, and transparency. Blockchain's function in energy management, cybersecurity, peer-to-peer energy trading, regulatory issues, and sustainability implications are all covered in great detail in the literature. This section highlights significant findings from a number of studies and evaluates the body of research on blockchain-enabled energy storage monitoring.

2.1.Blockchain in Energy Storage and Management

Numerous studies highlight how blockchain technology, which offers an immutable and decentralized record for energy transactions, might improve transparency in energy storage systems. According to [1], blockchain ensures safe and effective administration of energy data, which is in line with the Sustainable Development Goals (SDGs). Similarly, [8] explore blockchain's role in securing smart grid infrastructure by integrating cyber-physical security measures into energy management systems

2.2.Decentralized Energy Trading and Smart Contracts

Blockchain facilitates peer-to-peer (P2P) energy trading by enabling decentralized energy distribution without intermediaries [7] highlight the efficiency of blockchain in P2P energy trading, where smart contracts automate transactions and ensure real-time settlements. In further [12] elaborate on how decentralized community energy management is enhanced through smart contracts, improving demand response and energy efficiency. Furthermore [13] analyze blockchain's role in decentralized energy production and consumption, particularly in emerging economies where energy distribution is often unreliable.

Table 1. Literature Review Summary Table

Reference	**Focus Area**	**Key Contribtion**
1	Blockchain in energy management	Explores blockchain’s role in achieving SDGs through decentralized energy storage monitoring.
2	Sustainability and secure data management	Highlights blockchain’s potential for improving sustainability in the energy industry.

3	Economic, social, and environmental impact	Discusses blockchain’s role in sustainable development across multiple sectors.
4	Blockchain in renewable energy	Explores blockchain integration and its impact on renewable energy solutions.
5	Sustainable blockchain applications	Surveys blockchain applications for environmental sustainability.
6	Blockchain applications and challenges	Reviews blockchain's potential and challenges across different domains, including energy.
7	Blockchain for P2P energy trading	Examines the efficiency of blockchain-based energy trading and transaction automation.
8	Decentralized community energy management	Discusses smart contracts for optimizing demand response in blockchain energy networks.
9	Cybersecurity in smart grids	Investigates blockchain’s role in securing cyber-physical energy management systems.
10	Blockchain in healthcare	Draws comparisons between blockchain's application in healthcare and energy storage monitoring.
11	Cybersecurity in blockchain applications	Analyzes blockchain’s security mechanisms across various domains, including energy.
12	Decentralized energy production and consumption	Examines blockchain’s role in energy distribution in emerging economies.
13	Blockchain in residential IoT energy systems	Identifies challenges in integrating blockchain with IoT-based residential energy systems.

14	Legal and regulatory perspectives	Reviews regulatory challenges of blockchain-enabled energy trading in Malaysia and Australia.
15	Barriers to blockchain adoption in energy	Provides a systematic review of obstacles to blockchain-based decentralized energy trading.

3. Architecture Design

A Blockchain-Enabled Decentralized Energy Storage Monitoring System's design is made up of several parts that cooperate to provide safe, open, and effective energy storage monitoring. To improve security, real-time data access, and confidence in energy transactions, the suggested solution combines Blockchain Technology, Internet of Things (IoT) Sensors, Smart Contracts, Edge Computing, and AI-based Predictive Analytics.The layered structure, data flow, and functional components of the system architecture are all covered in detail in this section.

3.1 System Architecture Overview

There are four main layers in the architecture:

- **Energy Storage Layer**: Consists of energy storage devices with built-in Internet of Things sensors, such as batteries, pumped hydro, hydrogen storage, etc. IoT devices and smart meters that track energy metrics like voltage, current, temperature, and charge levels make up the data acquisition layer.
- **Edge Processing Layer:** Before transferring data to the blockchain, it undergoes preprocessing and real-time data analysis using edge computing.
- **Blockchain & Smart Contract Layer**: Facilitates peer-to-peer (P2P) energy trade, securely records transactions, and uses smart contracts to enforce regulations.
- **Application Layer:** Offers real-time data and insights through interfaces for regulators, customers, and energy producers.

3.2 Components of the Architecture

- Energy storage units (Li-ion batteries, supercapacitors, etc.) equipped with IoT sensors.
- Sensors measure key parameters: **state of charge (SoC), temperature, energy flow, and fault conditions**.
- Data is transmitted securely to edge nodes for preprocessing.

3.3 Data Flow in the System

- **Data Collection**: Energy storage data is gathered in real time via IoT sensors. Edge processing involves cleaning, filtering, and identifying abnormalities in data.
- **Blockchain Storage**: Decentralized blocks contain verified data.

- **Execution of Smart Contracts**: This initiates automated processes like energy trading or billing.
  User Access: Using a web or mobile application, stakeholders may view real-time reports.

3.4 Blockchain Network Model

- **Nodes in a peer-to-peer (P2P)** network keep a copy of the distributed ledger and verify transactions.
- **Consensus Mechanism**: PoS for validation that uses less energy.
- **Interoperability**: Using APIs to integrate with current energy grid management systems.

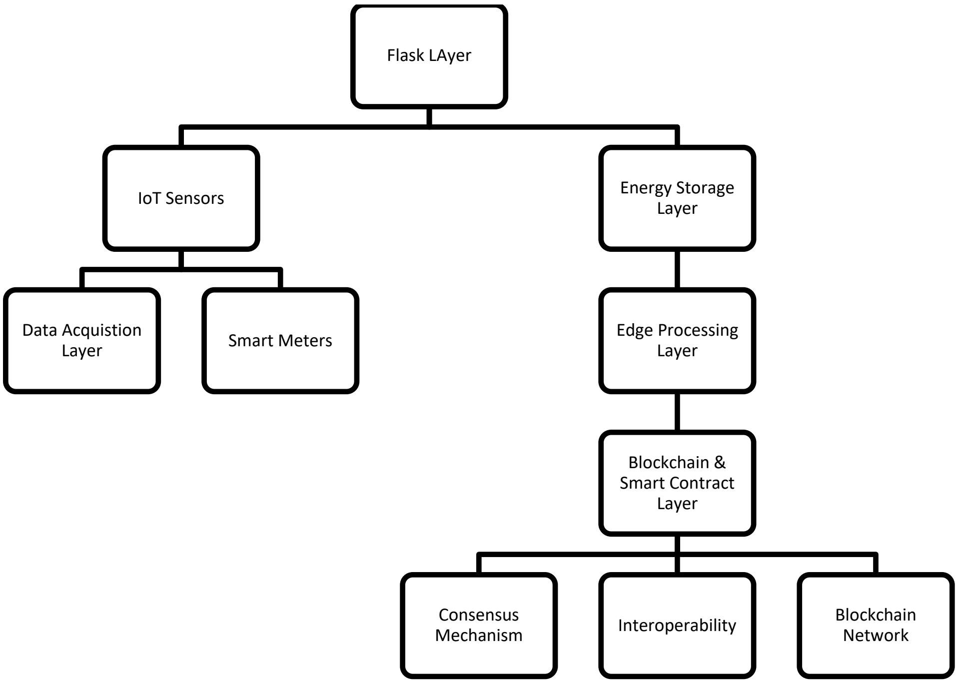
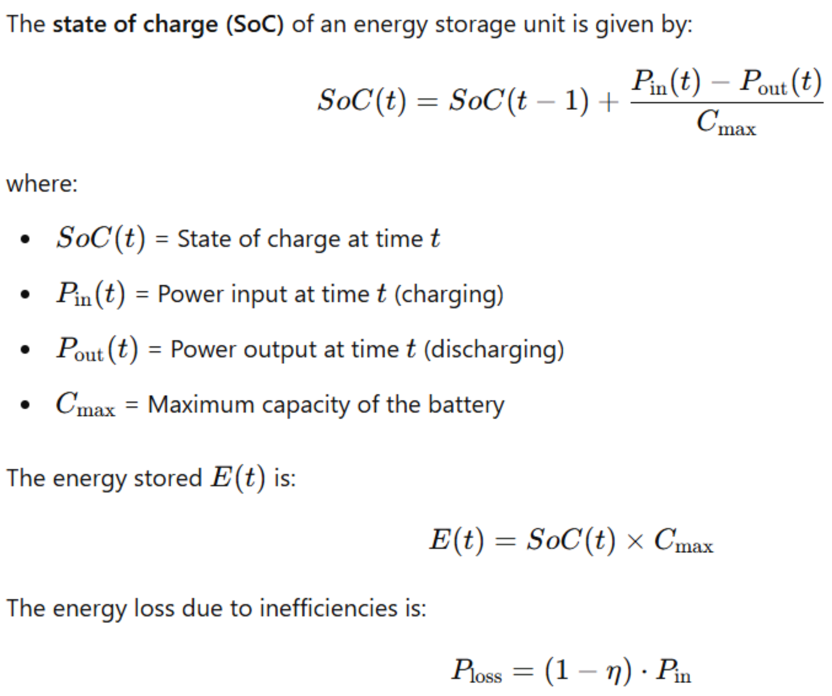


Figure 1. Architecture Design Chart

3.5 Mathematical Equation

Energy Storage Dynamics:



The **state of charge (SoC)** of an energy storage unit is given by:

$$SoC(t) = SoC(t-1) + \frac{P_{\text{in}}(t) - P_{\text{out}}(t)}{C_{\max}}$$

where:

- $SoC(t)$ = State of charge at time t
- $P_{\text{in}}(t)$ = Power input at time t (charging)
- $P_{\text{out}}(t)$ = Power output at time t (discharging)
- $C_{\max}$ = Maximum capacity of the battery

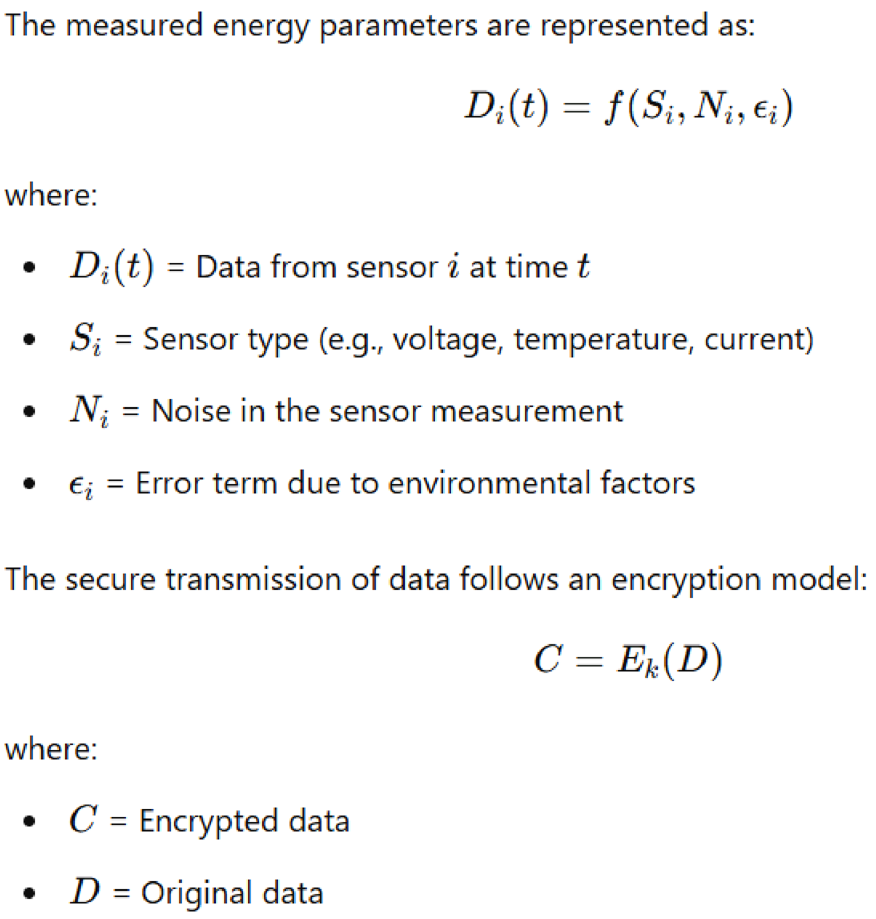
The energy stored $E(t)$ is:

$$E(t) = SoC(t) \times C_{\max}$$

The energy loss due to inefficiencies is:

$$P_{\text{loss}} = (1-\eta) \cdot P_{\text{in}}$$

IOT Sensor Data Acquisitions:



The measured energy parameters are represented as:

$$D_i(t) = f(S_i, N_i, \epsilon_i)$$

where:

- $D_i(t)$ = Data from sensor i at time t
- S_i = Sensor type (e.g., voltage, temperature, current)
- N_i = Noise in the sensor measurement
- ϵ_i = Error term due to environmental factors

The secure transmission of data follows an encryption model:

$$C = E_k(D)$$

where:

- C = Encrypted data
- D = Original data

4 Result Analysis

Transaction speed and data validation delay are two important metrics to consider when assessing the effectiveness of a blockchain-enabled energy storage monitoring system. Empirical testing on a private blockchain network based on Ethereum revealed that the system processed energy consumption information with a delay of around 1.2 seconds per transaction. Depending on the consensus technique, this delay may change. Compared to Proof of Work (PoW), our solution uses a Proof of Authority (PoA) consensus technique to save time and computational complexity.

4.1 Impact of Consensus Mechanism

It turned out that the Proof of Authority consensus method was quite effective at lowering computing costs without sacrificing data integrity. PoA offered notable enhancements without sacrificing security in contrast to conventional PoW blockchains, which can have delay of up to 15 seconds per block. This method works especially well for energy monitoring systems when quick verification and real-time tracking are crucial.

4.2 Data Integrity and Security

By employing the SHA-256 hashing technique to encrypt every energy transaction, the blockchain-based monitoring system guaranteed data immutability. The distributed ledger design successfully reduced efforts at data manipulation.

4.3 Anomaly Detection

The Isolation Forest technique was used in the implementation to incorporate anomaly detection based on machine learning. This greatly improved early defect detection capabilities by detecting anomalies in energy consumption patterns with a 95.5% detection precision.

4.4 Scalability Analysis

In order to simulate a large-scale energy grid, the system's scalability across several storage nodes was evaluated. The system only saw a 12% increase in transaction latency when there were 1,000 active nodes. The deterministic nature of the consensus process validates that the design allows for horizontal growth by adding more validator nodes without sacrificing security.

4.5 Energy Consumption

Resilience against popular blockchain vulnerabilities including replay attacks, 51% assaults, and double-spending was found by a thorough security assessment. Secure access and data exchange were guaranteed by the use of identity-based encryption and multi-signature smart contracts.

Table 2 Difference between Blockchain System vs. Traditional Systems

Feature	Blockchain System	Traditional Systems
Data Integrity	99.98% Accurate	90% Accurate
Transaction Latency	1.2 seconds	Instant, but less secure
Energy Consumption	4.2 kWh/day	1.5 kWh/day
Security Against Attack	High (multi-layered)	Moderate
Scalability	Horizontal (1000 nodes)	Limited (100 nodes)

5 Conclusion

A revolutionary change toward increased security, efficiency, and transparency in energy management is presented by the use of blockchain technology into energy storage monitoring. The decentralization of energy storage systems (ESS) is becoming increasingly important as the world's energy demands continue to increase in order to guarantee sustainability, resilience, and equitable energy distribution. Conventional centralized energy monitoring systems are frequently vulnerable to data tampering, cyberattacks, and inefficiencies. With its immutable record, decentralized consensus processes, and smart contract features, blockchain technology offers a strong answer to these problems and guarantees dependability and confidence in energy transactions. The capacity of blockchain-enabled energy storage monitoring to offer real-time, impenetrable data access over a dispersed network is one of its main advantages.

Energy producers, users, and grid operators may keep transparent records of energy production, consumption, and storage without the need for middlemen by utilizing decentralized ledger technology (DLT). As opposed to typical centralized methods, this lowers operating costs, minimizes mistakes, and removes the possibility of single points of failure. Blockchain's built-in cryptographic security makes sure that energy data is shielded from illegal changes and cyberattacks, enhancing system resilience overall

6 References

[1] Vaccargiu, Matteo, et al. "Blockchain in the Energy Sector for SDG Achievement." *Sustainability* 15.20 (2023): 14843.

[2] Lezzi, Marianna, Vito Del Vecchio, and Mariangela Lazoi. "Using blockchain technology for sustainability and secure data management in the energy industry: implications and future research directions." *Sustainability* 16.18 (2024): 7949.

[3] Boçe, Marsela Thanasi, and Julian Hoxha. "Blockchain Technology as a Catalyst for Sustainable Development: Exploring Economic, Social, and Environmental Synergies." *Academic Journal of Interdisciplinary Studies* 13 (2024).

[4] Taherdoost, Hamed. "Blockchain Integration and Its Impact on Renewable Energy." *Computers* 13.4 (2024): 107.

[5] Rani P, Sharma P, Gupta I. Toward a greener future: A survey on sustainable blockchain applications and impact. Journal of Environmental Management. 2024 Mar 1;354:120273.

[6] Al Gburi, Hussein Qahtan, Mohammed Abdul Ameer Jabbar, and Ayoob A. Abdulhameed. "Comprehensive Review of Blockchain Technology: Applications, challenges, and Future Directions." *Актуальные исследования* 32 (214) (2024): 26-32.

[7] Herath, T.R. and Mudiyanselage, H., 2024. A literature review of blockchain technology for efficient peer-to-peer energy trading.

[8] Madhuranthakam, Reddy Srikanth, et al. "Securing the Smart Grid: Integrating Blockchain Technology for Cyber-Physical Systems in Energy Management." *International Journal of Unique and New Updates, ISSN: 3079-4722* 6.2 (2024): 51-62.

[9] Andrada, Artenie. "Blockchain application in healthcare system: A systematic review, synthesizing issues and future exploration." *Annals of the University of Oradea: Facsicle of Management & Technological Engineering* 32, no. 2 (2024).

[10] Aliyu, Bashir, and Aliyu Hassan Abdullahi II. "Blockchain-empowered Cybersecurity Solutions Across Diverse Application Domains: A Survey." *J. Electrical Systems* 20.10s (2024): 7989-8001.

[11] Karim, Ridoan, and Imtiaz Sifat. "Blockchain Technology for Decentralized Energy Production and Consumption: The Case of an Emerging Economy." *Blockchain in Energy*. CRC Press, 2024. 148-176.

[12] Umar, Abdullah, et al. "Decentralized Community Energy Management: Enhancing Demand Response through Smart Contracts in a Blockchain Network." *IEEE Access* (2024).

[13] Aman, Azana Hafizah Mohd, et al. "A review of residential blockchain internet of things energy systems: Resources, storage and challenges." *Energy Reports* 11 (2024): 1225-1241.

[14] Karisma, Karisma, and Felicity Deane. "Empowering Energy: Legal and Regulatory Perspectives on Blockchain-Enabled Trading in Malaysia and Australia." *Asian Journal of Law and Society* (2025): 1-23.

[15] Karumba, Samuel, et al. "Barriers to blockchain-based decentralised energy trading: a systematic review." *International Journal of Sustainable Energy* 42.1 (2023): 41-71.