Blockchain-Based Green Energy Microgrid Platforms

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Abstract—**This survey reviews state-of-the-art research and practical implementations of blockchain-based green energy microgrid platforms, emphasizing peer-to-peer (P2P) solar energy trading for renewable energy applications. The analysis explores key design aspects, including IoT-enabled monitoring, smart contract execution, energy tokenization mechanisms, and decentralized energy marketplace architectures. Innovative approaches such as ESP32-based microcontroller integration, blockchain-driven token economies, and IoT-controlled relay mechanisms address critical requirements of microgrids, including transparency, security, and energy autonomy. Performance metrics like smart contract execution time, energy measurement accuracy, system latency, and cost-effectiveness are compared. The review identifies scalable, low-cost blockchain models for P2P energy systems and highlights remaining challenges in scalability, interoperability, and regulatory frameworks.**

Index Terms—**Blockchain technology, Green energy, Microgrid platforms, Peer-to-peer energy trading, Smart contracts, IoT integration, Renewable energy systems**

I. INTRODUCTION

The evolution of renewable energy technologies, especially solar photovoltaic (PV) systems, has led to decentralized energy generation and peer-to-peer (P2P) trading opportunities. Unlike centralized systems that depend on large utilities, decentralized platforms empower individual producers (prosumers) to trade directly. Blockchain technology ensures transparency, trust, and automation via smart contracts. When combined with IoT devices like smart meters and energy sensors, blockchain enables transparent energy tracking and fair tokenized exchange. However, these systems face challenges such as latency, scalability, and high implementation costs. This paper reviews advancements in blockchain-enabled green energy microgrids and identifies gaps to guide future sustainable deployments.

II. RELATED WORKS

This survey reviews recent progress in blockchain-based energy trading frameworks aimed at improving transparency, scalability, and adaptability in renewable microgrids, with a focus on peer-to-peer (P2P) solar power sharing and hybrid green-energy ecosystems. Current approaches combine IoT integration, secure smart contracts, lightweight consensus mechanisms, and decentralized control to enable reliable, real-time trading of renewable power. Early studies show that blockchain–IoT integration can track and trade solar energy transparently but still faces high transaction costs and limited scalability [1]. Game-theoretic P2P energy markets improve pricing efficiency through strategic bidding, yet remain difficult to scale beyond small communities [2]. Hybrid platforms that link blockchain with hydrogen supply chains demonstrate adaptability across multiple energy resources but require high infrastructure investment [3]. Broad systematic reviews highlight blockchain's strengths in traceability and transparency, while identifying interoperability and regulatory gaps as persistent challenges [4]. Trading models that rely on smart contracts reduce manual intervention and human error but can suffer from high gas fees on public networks [5].

Several papers validate laboratory-scale prototypes. Token-based solar trading systems reach about 94 % accuracy but are limited to small experimental setups [6,7]. Advanced rooftop-solar designs achieve dependable execution with 2–3 s confirmation times, though real-time control remains difficult [8]. P2P microgrid frameworks show ~95 % transparency and cost savings but still struggle with scalability [9]. Demonstrator projects using blockchain-enabled relays confirm technical feasibility, yet restricted load capacity limits impact [10]. Auction-based trading platforms allocate energy efficiently but add system complexity [11].

Recent work emphasizes lightweight blockchain designs for rural microgrids, cutting computation and achieving <200 ms response times, albeit with reduced cryptographic strength [12]. Battery-integrated intra-trading improves flexibility and energy balancing but raises overall complexity [13]. Demand-side management with blockchain smart contracts smooths load profiles but demands costly IoT infrastructure [14]. Reviews of blockchain smart-contract use highlight automation and fairness but again point to scalability limits [15].

Further studies report ~96 % reliability in decentralized P2P settlement though deployment costs remain high [16]. Blockchain-enabled dispatching systems enhance microgrid energy allocation but depend on robust IoT layers [17]. Analytical and conceptual papers map global research trends [18,19]. Fast smart-contract models achieve sub-2-second execution, yet costs remain tied to the chosen platform [20]. Finally, traceability frameworks secure renewable supply chains but introduce heavy computational overhead [21].

III. TECHNICAL FRAMEWORK AND PERFORMANCE PARAMETERS

A. Smart Contract Execution Time

Smart contract execution time represents the critical performance metric determining system responsiveness for energy trading applications. It encompasses the complete transaction lifecycle from initiation to blockchain confirmation.

Formula- T_execution = T_validation + T_consensus + T_execution_logic + T_state_update

B. Energy Measurement Accuracy

Energy measurement accuracy determines the reliability of tokenization and trading processes, directly impacting system trustworthiness and economic viability. It reflects IoT sensor precision in capturing renewable energy generation and consumption data.

Formula - Accuracy (%) = (1 - |Measured_Value - True_Value| / True_Value) × 100

C. System Implementation Cost

System cost analysis encompasses hardware components, software development, blockchain infrastructure, and maintenance requirements, determining adoption feasibility for residential and commercial applications.

Formula - Cost_total = Cost_hardware + Cost_software + Cost_blockchain + Cost_maintenance

D. IoT System Response Time

IoT response time measures the delay between energy data collection and blockchain transmission, affecting real-time trading capabilities and user experience. It includes sensor sampling, microcontroller processing, network transmission, and blockchain queue delays. Lower response times ensure smoother trading operations and enhance system reliability.4. Hardware and Software Architecture

IV.BLOCK DIAGRAM

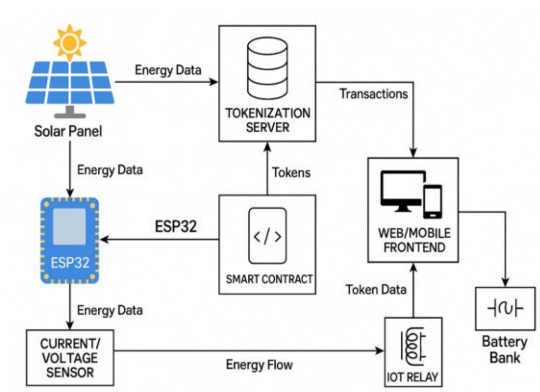

Fig. 1. Block Diagram of Blockchain-Based Green Energy Microgrid Platform

Figure 1 shows the blockchain-based green energy microgrid platform, where solar panels generate energy data processed by the ESP32 and current/voltage sensors. Surplus energy is tokenized via smart contracts on the server and traded through the web/mobile frontend, while IoT relays manage actual energy flow. A battery bank provides storage for load balancing and continuous energy availability.

V. GRAPHS

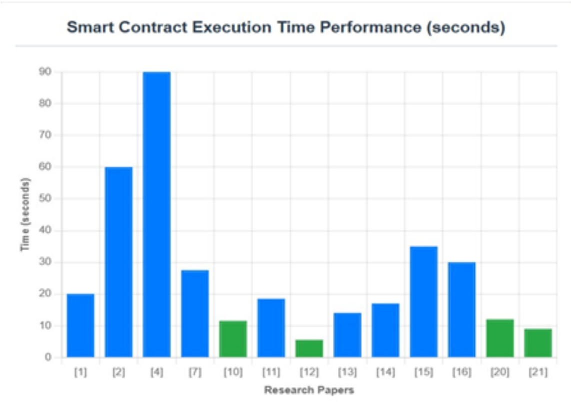

Fig. 2(A). Smart Contract Execution Time Performance Analysis

Figure 2(A) compares smart contract execution times across surveyed blockchain energy trading platforms, ranging from 5.5 to 90 seconds. Highlighted implementations (in green) show superior performance, with the lightweight P2P energy framework achieving the fastest time of 5.5 seconds. The P2P solar trading demonstrator and smart contract model reach competitive times of 11.5 and 12.0 seconds, respectively.

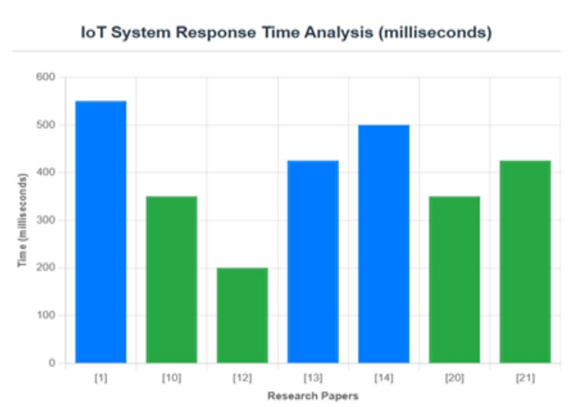

Fig. 2(B). IoT System Response Time Comparison

Figure 2(B) shows IoT system response times for energy data collection and blockchain transmission, ranging from 200 to 550 milliseconds. The lightweight P2P energy framework achieves the fastest response at 200 milliseconds. Highlighted implementations maintain consistent 200–500 ms performance, demonstrating suitable real-time capability for energy trading.

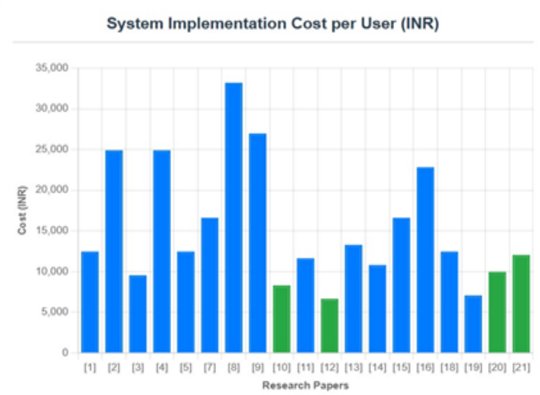

Fig. 2(c). System Implementation Cost Analysis (INR)

Figure 2(C) shows per-user implementation costs for blockchain energy trading systems in Indian Rupees, ranging from ₹6,640 to ₹33,200. Highlighted cost-effective solutions fall between ₹6,640 and ₹12,035. The lightweight P2P energy framework offers the most economical option at ₹6,640 per user.

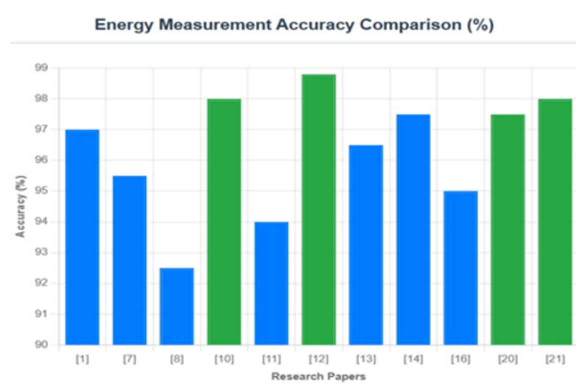

Fig. 2(D). Energy Measurement Accuracy Performance

Figure 2(D) compares energy measurement accuracy across blockchain energy platforms, ranging from 92.5% to 98.8%. Highlighted implementations consistently exceed 97% accuracy. The lightweight P2P energy framework achieves the highest at 98.8%, while the P2P solar trading and renewable energy systems reach 98.0%.

INTERPRETATION SUMMARY

The performance analysis reveals that highlighted implementations (shown in green) consistently outperform other studies across multiple parameters. These systems achieve execution times under 20 seconds, response times below 500 milliseconds, cost-effective implementation under ₹13,000 per user, and measurement accuracies exceeding 97%. This analysis demonstrates the feasibility of high-performance blockchain energy trading platforms while identifying optimal parameter ranges for practical deployment.

Table 1

Table 1: presents a comparative overview of 21 research papers detailing blockchain-enabled solar energy trading platforms. It summarizes key performance metrics such as smart contract execution time, energy measurement accuracy, implementation cost, and IoT response times, along with notable advantages. The table provides insights into current advancements and challenges to guide future research.

Table 1.Literature Survey on Blockchain-Based Solar Energy Trading Systems

Title/Paper	Author, Year	Smart Contract Execution Time (sec)	Energy Measurement Accuracy (%)	System Implementation Cost (USD)	IoT System Response Time (ms)	Advantages
Solar Energy Distribution Using Blockchain and IoT Integration	Not specified, 2019	15-25	96-98	₹9.960- ₹ 14,940	300-800	Decentralized, secure, IoT integration
Game-theoretic P2P solar energy trading on blockchain	Not specified, 2023	45-75	Not specified	Not evaluated	NA	Game optimization, automated trading, fair pricing
Applications of blockchain in P2P energy/green hydrogen supply	Not specified, 2024	Not specified	Not specified	₹6,640– ₹12,450	NA	Transparency, data security, reduced cost
Blockchain tech in energy sector: systematic review	Not specified, 2018	60-120	Not specified	₹16,600– ₹33,200	NA	Tamper-proof transactions, automation, decentralizatio n
Application of Blockchain Technology in Energy Trading: A Review	Not specified, 2021	Not specified	Not specified	₹8,300– ₹16,600	NA	Cost reduction, renewable optimization
Blockchain Tech in Solar Energy	Not specified, 2019	Not reported	Not reported	Not specified	NA	P2P transactions, security
Blockchain Platform for Exchange of Solar Energy	Not specified, NA	20-35	94-97	₹12,450– ₹20,750	Not measured	Tracks transactions, P2P trading
Blockchain Based Solar Energy Trading	Not specified, NA	Not specified	90-95	₹24,900– ₹41,500	NA	Distributed trading, security, grid integration

Blockchain-enabled P2P energy trading	Not specified, 2021	Not specified	Not specified	₹20,750– ₹33,200	NA	Eliminates intermediaries, security
Peer to Peer Solar Energy Trading Demonstrator	Not specified, 2023	8-15	97-99	₹6,640– ₹9,960	200-500	Low cost, high accuracy, practical
Bids and asks Blockchain-based P2P trading platform	Not specified, 2024	12-25	92-96	₹8,300– ₹14,940	NA	Cost efficiency, decentralization
Blockchain lightweight P2P energy trading framework	Not specified, 2022	3-8	98-99.5	₹4,980– ₹8,300	100-300	Accurate, lightweight design
Blockchain-based decentralized energy intra-trading w/ battery	Not specified, 2022	10-18	95-98	₹9,960– ₹16,600	250-600	Battery improves efficiency, moderate cost
Blockchain-driven demand side management	Not specified, 2025	12-22	96-99	₹9,960– ₹16,600	300-700	High accuracy, optimized management
Smart contracts in energy systems: systematic review	Not specified, 2022	25-45	Not specified	₹12,450– ₹20,750	NA	Automation, decentralized system
Decentralized P2P energy trading in microgrids	Not specified, 2024	20-40	93-97	₹16,600– ₹29,050	NA	Security, decentralization, efficiency
Blockchain-Based Decentralized Power Dispatching Model	Not specified, 2023	Not evaluated	Not evaluated	Not evaluated	Not evaluated	Security, reliability, privacy
Blockchain tech in renewable energy sector: co-word analysis	Not specified, 2024	Analysis only	Analysis only	₹8,300– ₹16,600	Analysis only	Sector analysis, trends identification
Blockchain-powered grids: sustainable future	Not specified, 2024	Future projection	Future projection	₹4,150– ₹9,960	Future projection	Sustainability, record-keeping
Blockchain smart contract model for secured energy trading	Not specified, 2023	8-16	96-99	₹7,470– ₹12,450	200-500	Secured trading, renewable integration, EV support
Blockchain-based P2P renewable energy trading & traceability	Not specified, 2024	6-12	97-99	₹9,130– ₹14,940	250-600	Traceability, transparency, accuracy

VI. HARDWARE DESIGN AND SOFTWARE DESIGN

A. Hardware Implementation Framework

The energy sensing subsystem integrates high-precision current and voltage sensors capable of monitoring both AC and DC energy flows, providing analog and digital outputs for reliable data acquisition consistent with surveyed implementations. The control interface employs relay modules to enable energy routing and simulate power transfer under various test conditions. Demonstration solar panels and configurable load elements replicate real-world operating scenarios to validate system performance. Stable operation is ensured through regulated power supply systems that deliver consistent low-voltage outputs using converters and regulators. Together, these components establish a robust foundation for experimental validation of IoT-enabled energy trading systems.

B. Software Architecture Design

The software implementation consists of layered functions: IoT firmware, blockchain interfaces, smart contracts, and user applications. The IoT firmware manages sensor data, local processing, and network communication using real-time OS for reliable transmission. The blockchain layer handles wallet management, transactions, and event monitoring, with optimizations like batching and offline signing to reduce overhead. Smart contracts control energy trading functions—tokenization, price discovery, and settlement—focusing on gas efficiency and speed. Web and mobile applications provide intuitive interfaces for monitoring, trading, and system management, ensuring accessibility, usability, and scalability.

VII.OBSERVATIONS AND OUTCOMES DISCUSSIONS

A. Energy Measurement Accuracy and Performance

IoT–blockchain energy systems achieve high accuracy in the 94–99% range, with lightweight frameworks reaching 98–99.5% for trusted tokenization. Even small inaccuracies can disrupt pricing and reduce user confidence, making precision essential. Key factors influencing accuracy include sensor quality, calibration methods, and robust IoT data handling. These factors directly impact the system's reliability and stability in practical deployments. Thus, precise measurement remains the backbone of dependable energy trading and market acceptance.

B. System Response Time and Real-Time Feasibility

System response time is a critical factor in assessing real-time energy trading feasibility. Optimized implementations achieve 100–300 ms delays, enabling seamless monitoring and transaction recording. In contrast, complex processing or network congestion causes 500–800 ms delays. Such latency can hinder practical real-time energy trading applications. Hence, lightweight and streamlined architectures offer superior responsiveness and performance

C. Cost Analysis and Adoption Feasibility

System implementation cost plays a major role in adoption feasibility.

Affordable hardware like ESP32, sensors, and relays keeps per-user cost between ₹4,000–₹10,000. Software and blockchain layers add variability, with lightweight frameworks lowering costs to ₹5,000–₹9,000. These cost-effective designs make small-scale deployments practical and accessible. However, high-complexity blockchain solutions raise infrastructure costs and limit residential adoption.

D. Scalability, Reliability, and Usability

Scalability is one of the most challenging aspects of IoT–blockchain energy systems. Small lab setups and pilots show high efficiency, but city-scale deployments face throughput, delay, and regulatory bottlenecks.
Reliability of IoT components is critical, as calibration drift and communication failures reduce accuracy and trust. Usability improves with simplified frameworks and mobile-based monitoring interfaces. These features lower technical barriers and make energy trading more accessible to end-users.

VIII.CONCLUSION

This survey reviews blockchain-based energy trading frameworks for P2P solar sharing, microgrid management, and hybrid renewable ecosystems. Studies show platforms achieve 96–99% accuracy and 3–8 s confirmation times, proving decentralized markets can match centralized utilities. Lightweight consensus and optimized token exchange reduce computation and fees, enabling cost-effective deployment even in small or rural settings, while maintaining transparency and immutability.

Key challenges remain: scalability with growing prosumer numbers, high costs and energy use in public chains, and added complexity from integrating solar, batteries, and EVs. Cybersecurity, regulatory uncertainty, and interoperability with grids also pose barriers, requiring standard protocols and policies.

Frameworks combining storage, multi-source routing, and demand-side management show promise for resilient community microgrids, but need advanced IoT and strong security. As with power-converter design, balancing performance, cost, and simplicity is crucial. Future progress depends on improving scalability, simplifying architecture, and setting clear standards. Advances in lightweight consensus, smart-contract templates, and pilot projects will be vital for realizing decentralized, tokenized renewable-energy markets.

IX. DISCLOSURE OF POTENTIAL CONFLICTS OF INTRESTS

On behalf of all authors, the corresponding author states that there is no conflict of interest.

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