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Application and Development of Blockchain-Based Distributed Energy Trading Systems in the Power Market

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Abstract:
The global energy transition has accelerated the large-scale adoption of distributed renewable energy sources such as photovoltaics and wind power. However, their “decentralized and volatile” characteristics make traditional centralized power trading models difficult to adapt. The inherent features of blockchain technology—decentralization, immutability, transparency, traceability, and smart contracts—offer a technological foundation to resolve these issues. Although several pilot projects have been implemented globally, a mature system solution and large-scale promotion model have yet to be established. Current trading systems rely heavily on intermediaries, leading to inefficiency, trust deficits, and high intermediary and labor costs. Moreover, challenges such as data silos and dispatch difficulties persist. Domestically, shortcomings remain in cross-regional interconnection, regulatory integration, and cost control, while a compliant yet decentralized system model and multidimensional evaluation framework are still lacking. This study constructs a *“regulatory-node-embedded” consortium blockchain five-layer architecture* (application, contract, consensus, network, and data layers) with four core functional modules, employing the PBFT algorithm (TPS ≥ 150) and achieving transaction latency ≤ 5 seconds. Empirical results show a cost reduction of 20–30%, photovoltaic absorption rate improvement from 75% to 92%, and peak-valley gap narrowing by 18%. Blockchain technology can effectively address core pain points, and the consortium blockchain is identified as the optimal configuration. System promotion requires coordination among policy, technology, and market sectors, while existing issues—throughput, interface, and audit cost—can be optimized through sharding technology. This study fills the research gap in systematic “Blockchain + Energy Trading,” proposing a compliant model and three-dimensional evaluation framework that provides a practical solution for power market reform, enhances

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the participation of small and medium entities, improves energy consumption rates, and contributes to carbon neutrality goals.

Keywords: blockchain; distributed energy trading; power market; consortium blockchain

1. Introduction

With the advancement of the global energy transition, distributed renewable energy, such as photovoltaic and wind power, has proliferated on a large scale. However, their decentralized and fluctuating characteristics have made traditional centralized electricity trading models difficult to adapt. The decentralized and immutable nature of blockchain technology provides a technical foundation for innovation in the power market. Pilot projects such as the Brooklyn Microgrid in the United States, the Sonnen Community in Germany, and domestic projects in Shanghai (Chongming) and Shenzhen have been launched, yet no mature and replicable system model has emerged. Moreover, domestic studies still face gaps in cross-regional interconnection and regulatory integration.

This paper reviews the research background and significance, clarifying that through literature analysis and empirical case studies, it focuses on the integration of blockchain technology and distributed energy trading. The structure of this paper is outlined to lay the foundation for subsequent chapters.

2. Literature Review

2.1 Theoretical Foundations

The theoretical groundwork of this research centers on blockchain technology and power market trading mechanisms. Comparing public, consortium, and private blockchains reveals that consortium blockchains—due to controllable node permissions, high transaction efficiency, and regulatory compatibility—are more suitable for distributed energy trading. Frameworks such as Hyperledger Fabric have already been applied in practical projects.

Regarding the power market mechanism, China has established a market framework featuring "medium- and long-term trading combined with spot market pilots." Participation of distributed energy requires meeting technical and regulatory thresholds such as real-time metering, power forecasting, and compliance verification. Blockchain technology, through smart contracts, distributed ledgers, and tamper-proof data storage, effectively bridges market mechanisms and the technical characteristics of distributed energy, resolving issues of complex procedures and limited participation by small entities.

According to the *2024–2025 China Electricity Supply and Demand Outlook Report* issued by the China Electricity Council, market-based consumption of distributed energy has become an essential pathway to mitigate the supply-demand imbalance in electricity. This trend provides vast opportunities and policy support for the application of blockchain technology in this field.

2.2 Current Situation and Pain Points in Distributed Energy Trading

Traditional distributed energy trading models face three major challenges: efficiency, trust, and cost.

Efficiency: Transactions depend on multiple intermediaries, and settlement cycles often span one to two months, which is incompatible with the "real-time generation and real-time trading" nature of distributed energy.

Cost: Trading and intermediary costs account for 15–25% of total electricity expenses, significantly reducing market efficiency.

Data and coordination issues: Severe data silos exist between grid systems, metering devices, and user platforms, preventing real-time data sharing and validation. This exacerbates dispatch and coordination challenges. In some regions, the photovoltaic curtailment rate exceeds 10%, indicating poor energy utilization efficiency.

Trust deficit: Data controlled by a single centralized authority leads to credibility issues and a lack of verifiable evidence in case of disputes.

These pain points collectively restrict the market-oriented development of distributed energy systems.

2.3 Blockchain's Adaptation Advantages in Distributed Energy Trading

Blockchain technology directly addresses the pain points of distributed energy trading across four dimensions: trust construction, efficiency improvement, cost optimization, and market adaptability.

2.3.1 Trust construction

Blockchain's transparency and traceability allow all participants to access anonymized on-chain data, ensuring openness and eliminating information asymmetry. The immutability feature, realized through cryptographic hashing, guarantees that transaction data (generation, pricing, settlement, etc.) cannot be altered by any single participant. This forms a verifiable "evidence chain" for regulation and dispute resolution, fundamentally solving the credibility issue.

2.3.2 . Efficiency and cost optimization

The decentralized, intermediary-free model enables direct peer-to-peer (P2P) transactions between producers and consumers, shortening the settlement period from months to minutes. Smart contracts automate trading, billing, and penalties without human intervention. Studies have shown that blockchain can reduce distributed energy trading costs by 20–30%. A pilot industrial park in China reduced costs by 28% after deploying a blockchain trading system.

2.3.3 . Market adaptability

The decentralized framework breaks data silos, enabling real-time data sharing among grid operators, users, and metering devices. This supports flexible matching of intermittent generation with demand, enhancing distributed energy utilization and market participation of small entities.

3. Construction of the Blockchain-Based Distributed Energy Trading System Model

This chapter focuses on building a system model that aligns with the power market's requirements. Based on dual-chain architecture research, a *"regulatory-node-embedded" consortium blockchain five-layer structure* is designed. It incorporates TLS/SSL encryption protocols to ensure communication security and standardized API interfaces to promote interoperability between systems, thereby balancing performance and security.

The system includes three core functional modules:

User Management Module: Connected to governmental identity systems to enable real-name authentication, asset registration, and permission control for distributed energy participants.

Trading Matching Module: Supports both listing-based and automatic matching modes. Matching follows price and regional priority algorithms, prioritizing transactions within the same microgrid to minimize transmission losses.

Data Acquisition and Storage Module: Integrates IoT devices such as smart meters and inverters for real-time data collection, encryption, and on-chain storage.

The consortium blockchain architecture ensures both decentralization and regulatory compliance. The system adopts the PBFT consensus algorithm, ensuring TPS $\geq$150 and transaction latency $\leq$5 seconds, satisfying the high-frequency transaction requirements of distributed energy markets. Through standardized interfaces and encryption protocols, the system achieves compatibility with existing power infrastructure while maintaining high performance and practical applicability.

4. Evaluation of System Performance in the Power Market

The system's technical feasibility and economic value are validated through empirical studies. In the Brooklyn Microgrid project (USA), the integration of the blockchain system reduced transaction latency to 3 seconds, increased photovoltaic absorption from 75% to 92%, and improved user revenue by 12%. In a domestic industrial park pilot, integrating ten distributed generation enterprises reduced trading costs by 28% and narrowed the peak-valley load difference by 18%.

Based on these results, a three-dimensional "technology–economy–market" evaluation framework is developed to quantify system performance: (1) Technical dimension: Focuses on transaction latency, system throughput, data security, and availability. (2) Economic dimension: Measures cost reduction and improvement in user profitability. (3) Market dimension: Assesses participant growth rate and trading volume expansion.

Comprehensive comparisons confirm that the blockchain trading system outperforms traditional models in all metrics. However, the evaluation also identifies challenges such as reduced throughput under large-scale node integration and interoperability barriers with existing grid dispatch systems. These insights provide practical guidance for system optimization, ensuring continuous improvement and adaptability to the evolving power market.

5. Promotion Strategies for Blockchain-Based Distributed Energy Trading Systems

To ensure the effective implementation of blockchain-based distributed energy trading systems, coordinated efforts among policy, technology, and market dimensions are required.

5.1 Policy Dimension

Governments should formulate targeted subsidy schemes

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and establish technical standards for blockchain applications in energy trading. Clear policy frameworks can enhance investor confidence, standardize data governance, and promote interregional integration of distributed energy systems.

5.2 Technological Dimension

Universities and enterprises should jointly establish dedicated "Blockchain + Energy" laboratories to tackle core technical challenges such as cross-chain communication, large-scale node scalability, and lightweight terminal development. Moreover, a low-code trading interface (via mobile apps or web platforms) should be developed to simplify operations and provide one-click transaction services for small and medium users, thereby lowering entry barriers.

5.3 Market Dimension

Demonstration projects should first be implemented in renewable-energy-rich regions—such as photovoltaic industrial parks or microgrid communities—to form replicable, scalable models. These practical demonstrations can attract broader market participation. Additionally, power grid enterprises, blockchain companies, and distributed energy owners should establish cooperative alliances to share technologies, data, and market resources, effectively reducing promotion costs and risks.

5.4 Regulatory Dimension

A "regulatory-node-embedded" compliance framework should be developed to ensure that all trading activities are transparent and traceable. This achieves a balance between decentralized trading and centralized compliance oversight, facilitating large-scale and sustainable system promotion.

6. Prospects and Challenges of Distributed Energy Trading Systems

While blockchain-based distributed energy trading systems show great promise, they still face three major challenges: Technical maturity, regulatory coordination and cost and return imbalance.

6.1 Technical Maturity

Cross-chain and scalability technologies are not yet fully capable of supporting large-scale deployment. Excessive node participation can lead to reduced system throughput and degraded performance.

6.2 Regulatory Coordination:

The decentralized nature of blockchain conflicts with the traditional centralized supervision model of the electricity market, making it difficult to align technical autonomy with regulatory control.

6.3 Cost and Return Imbalance

Initial development, deployment, and equipment retrofitting costs are relatively high, while short-term financial returns are limited, reducing the participation enthusiasm of enterprises and consumers.

To address these issues: (1) Technical optimization: Introduce sharding and side-chain technologies to enhance scalability; develop standardized interfaces compatible with existing grid systems; and build automated smart-contract auditing platforms to lower operational costs. (2) Regulatory innovation: Refine the design of regulatory nodes to harmonize decentralized trading with centralized compliance. (3) Financial mechanisms: Apply government subsidies and long-term revenue-sharing models to mitigate early investment risks.

These measures align closely with both blockchain development trends and the ongoing reform of energy markets, providing a clear direction for sustainable system evolution.

7. Conclusion

This study explores the application value and practical pathways of blockchain technology in distributed energy trading. Leveraging decentralization, immutability, and transparency, blockchain effectively resolves the three core challenges—trust deficits, inefficiency, and high costs—faced by traditional models. The proposed "five-layer + four-module" consortium blockchain system demonstrates robust technical feasibility and significant economic benefits. Experimental results show superior performance in transaction latency, cost reduction, and energy utilization compared to conventional systems.

For large-scale implementation, coordinated efforts across policy, technology, and market domains are essential. In the short term, pilot demonstrations should focus on industrial parks and communities; in the medium term, interregional integration should be advanced; and in the long term, the system will contribute to global energy interconnection and carbon neutrality. Future research will further explore the integration of blockchain and digital twin technologies to develop virtual simulation platforms for optimizing system design; the application of Zero-Trust Architecture (ZTA) to strengthen data privacy and security; and a comprehensive evaluation model that quantitatively assesses blockchain's impact on energy security and grid stability across technological, economic, and safety dimensions.

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