RADemics

Blockchain-Enabled P2P Energy Trading and Decentralized Grid Control for IoT-Integrated Smart Power Networks

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Abstract

The rapid digitalization of energy markets, coupled with the rise of decentralized power generation, has necessitated innovative solutions for secure, transparent, and scalable energy trading. Blockchain technology, integrated with P2P energy trading and IoT-enabled smart grids, presents a transformative approach to decentralized energy management. Challenges related to scalability, interoperability, transaction throughput, and security must be addressed to enable large-scale adoption. This book chapter explores advanced blockchain-enabled mechanisms, including Layer 2 scaling solutions, cross-chain communication, and AI-driven smart contract optimization, to enhance the efficiency of energy trading networks. The role of blockchain in managing renewable energy certificates (RECs) and carbon credits was also examined, highlighting tokenization as a means to improve market liquidity, transparency, and regulatory compliance. Additionally, a comparative analysis of consensus mechanisms and throughput optimization techniques was provided, offering insights into the trade-offs between security and scalability. The integration of AI and machine learning in smart contracts was discussed as a key enabler for predictive energy trading, automated market adjustments, and fraud detection. Future research directions focus on hybrid blockchain models, cross-chain interoperability, and sustainable energy tokenization frameworks. The findings of this chapter contribute to the development of a highly efficient, decentralized, and resilient smart power ecosystem, paving the way for the next generation of blockchain-based energy markets.

Keywords: Blockchain scalability, P2P energy trading, smart contract optimization, cross-chain interoperability, tokenized energy assets, decentralized grid control.

Introduction

The integration of blockchain technology into P2P energy trading and decentralized grid control has emerged as a transformative approach to enhancing the efficiency, security, and transparency of modern power networks [1]. With the increasing adoption of renewable energy sources and the rise of prosumers entities that both consume and generate electricity the traditional centralized energy market model faces significant challenges, including inefficiencies in energy distribution, high transaction costs, and lack of real-time market responsiveness [2,3]. Blockchain, as a decentralized and immutable ledger, provides a trustless infrastructure where energy transactions can be securely recorded, verified, and executed without reliance on intermediaries [4]. The adoption of smart contracts further automates trading processes, enabling seamless energy exchanges between producers and consumers in real-time [5-8]. Its potential, blockchain-based energy trading faces critical challenges related to scalability, interoperability, and transaction throughput, necessitating the development of advanced optimization strategies to ensure its feasibility for large-scale adoption [9].

Scalability remains one of the primary obstacles to the widespread implementation of blockchain-enabled energy trading. Conventional blockchain networks, such as Bitcoin and Ethereum, suffer from limited transaction processing speeds and high computational costs, making them unsuitable for handling high-frequency microtransactions in energy markets [10]. The inherent constraints of blockchain consensus mechanisms, including proof-of-work (PoW) and proof-of-stake (PoS), lead to network congestion and increased transaction latency [11,12]. To address these issues, Layer 2 scaling solutions, such as state channels, rollups, and sidechains, have been developed to enhance transaction throughput while maintaining the security and decentralization of the underlying blockchain network. These scaling techniques enable off-chain computation and reduce on-chain data storage requirements, significantly improving the efficiency of energy trading platforms [13]. Additionally, the adoption of hybrid blockchain architectures, combining public and private blockchains, offers a promising approach to balancing scalability with security and accessibility. By leveraging these advancements, blockchain can facilitate real-time energy transactions with minimal latency, supporting the growth of decentralized power networks [14].

Interoperability between multiple blockchain networks was another crucial challenge in the development of decentralized energy markets. Existing energy trading platforms often operate on isolated blockchain ecosystems, limiting their ability to interact and exchange assets across different networks [15]. This lack of interoperability leads to market fragmentation, reduced liquidity, and inefficiencies in cross-platform transactions [16]. Cross-chain communication protocols, such as blockchain bridges, hashed time-locked contracts (HTLCs), and interoperability frameworks like Polkadot and Cosmos, enable seamless data and asset transfers between disparate blockchain networks [17]. These solutions enhance market connectivity, allowing energy producers and consumers to participate in a unified, decentralized energy ecosystem [18]. Integrating blockchain with IoT devices and smart meters enhances data accuracy and automation in energy trading. IoT sensors provide real-time data on energy generation, consumption, and grid conditions, which can be securely recorded on the blockchain and utilized for automated trading decisions [19]. This convergence of blockchain and IoT fosters a more resilient and adaptive energy trading framework, capable of responding dynamically to market fluctuations [20].