МАТЕМАТИКА И МАТЕМАТИЧЕСКО ОБРАЗОВАНИЕ, 2025
MATHEMATICS AND EDUCATION IN MATHEMATICS, 2025
Proceedings of the Fifty-Fourth Spring Conference
of the Union of Bulgarian Mathematicians
Varna, March 31 – April 4, 2025

REVOLUTIONIZING PEER-TO-PEER ENERGY TRADING WITH BLOCKCHAIN TECHNOLOGY

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This paper examines the application of blockchain technology in the energy sector, particularly in peer-to-peer (P2P) energy trading, which is a way for users with distributed energy resources (DERs) to exchange energy with each other without relying on a centralized authority. Blockchain technology is an innovative and disruptive tool that can enable P2P energy transactions and smart contracts, and improve the efficiency, transparency, security, and sustainability of energy services. However, blockchain technology adoption also faces many challenges and barriers, such as the technical maturity and scalability of blockchain solutions and the integration of blockchain with other technologies. The paper aims to provide an overview of the literature on blockchain technology in the energy sector and to analyze the main application areas, benefits, challenges, and opportunities of blockchain technology in this field. In addition, it presents a theoretical model showcasing a P2P energy trading system utilizing blockchain technology.

Keywords: blockchain, peer-to-peer, distributed energy resources, energy trading, Internet Of Things, Smart Contracts, Decentralized Systems, Energy Management

ПРЕДСТАВЯНЕ НА ИНОВАТИВНИ ИДЕИ В ТЪРГОВИЯТА С ЕНЕРГИЯ МЕЖДУ РАВНОПОСТАВЕНИ ПАРТНЬОРИ С БЛОКЧЕЙН ТЕХНОЛОГИЯ

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В този документ се разглежда приложението на блокчейн технологията в енергийния сектор, по-специално в търговията с енергия между равнопоставени потребители (P2P), която е начин потребителите с разпределени енергийни ресурси (DER)

https://doi.org/10.55630/mem.2025.54.069-077
2020 Mathematics Subject Classification: 68M14, 68U35, 68N01, 68P20.

да обменят енергия помежду си, без да разчитат на централизиран орган. Блокчейн технологията е иновативен и революционен инструмент, който може да даде възможност за P2P енергийни транзакции и интелигентни договори и да подобри ефективността, прозрачността, сигурността и устойчивостта на енергийните услуги. Приемането на блокчейн технологията обаче се сблъсква и с много предизвикателства и пречки, като например техническата зрялост и мащабируемостта на блокчейн решенията и интегрирането на блокчейн с други технологии. Статията има за цел да направи преглед на литературата относно блокчейн технологията в енергийния сектор и да анализира основните области на приложение, ползите, предизвикателствата и възможностите на блокчейн технологията в тази област. В допълнение, той представя теоретичен модел, показващ P2P система за търговия с енергия, използваща технологията блокчейн

Ключови думи: Блокчейн, Равнопоставен обмен, Разпределени енергийни ресурси, Търговия с енергия, Интернет на нещата, Умни договори, Разпределени системи, Управление на енегрията

1. Introduction. The emergence of blockchain technology has unlocked new opportunities across various industries, including the energy sector. This technology, which serves as the foundation for digital currencies, has the potential to transform energy trading and exchange. According to a government and private sector report, blockchain technologies have the potential to revolutionize various sectors by eliminating intermediaries, promoting transparency [9]. The focus of this paper is the utilization of blockchain technology in peer-to-peer (P2P) energy trading. We must emphasize that this paper is researching the technological approach, considering that the infrastructure and the law in the country, where it will be implemented, allow this.

One of the areas where blockchain technology can have a significant impact is renewable energy sources (RES) are rapidly transforming energy systems, driven by privatization, sector unbundling, and policy initiatives. However, these RES face challenges due to their fluctuating nature and dependence on weather conditions. This necessitates more flexibility measures, such as fast-acting supply, demand response, and energy storage services, for safe operation and stability. The transformation is further amplified by distributed energy resources (DERs) and the impending digital era marked by the widespread deployment of smart meters [2]. Peer-to-peer energy trading, an emerging approach, enables users with DERs to trade energy directly, reducing the need for centralized authorities. This method can improve efficiency, transparency, and sustainability of energy services. However, implementing such a system is not without its challenges.

To address these challenges, blockchain technology can provide a decentralized and secure solution. With its decentralized nature and ability to execute smart contracts, it has the potential to revolutionize P2P energy trading by addressing several challenges, including the need for secure and transparent transactions. Blockchain technology is increasingly being used in energy commodity trading, where transactions are packaged into blocks and settled using a common market mechanism. Blockchain technology can help companies achieve unprecedented efficiency, lower transaction costs, and reduce risks, ultimately improving the efficiency of energy commodity trading [10]. It can also disrupt market operations, enhance the control of distributed energy systems, and affect revenues and tariffs. Blockchain can facilitate communication within smart devices, data transmission, and asset management while protecting privacy and identity. However, blockchain adoption faces challenges including technical maturity, stakeholder interests, incentive mechanisms, regulatory frameworks, and integration with other technologies like IoT, AI, and smart contracts. It is important to understand the current and future prospects of blockchain technology in the energy sector [10].

Therefore, blockchain technology can enable a new paradigm of energy trading that is more efficient, transparent, and sustainable. Distributed ledger technologies and smart contracts allow energy generators to trade with consumers and retailers without middlemen. Autonomous trading agents find the best deals and record agreements in the blockchain, executing them on time. Payments are automated, and transaction data is accessible through a single point of access, the distributed ledger. However, implementing blockchain technology in the energy market would require significant regulatory changes and could impact the role of intermediaries, such as brokers, exchanges, and trading agencies. Despite the potential for blockchain to transform the energy market structure, overcoming significant technical challenges and roadblocks is necessary to realize this vision in practice [2].

This paper provides a theoretical review of the current literature on the application of blockchain technology in the energy sector, with the aim of answering the following research question:

- How does blockchain technology enable peer-to-peer energy trading in decentralized networks?

This paper explores how blockchain technology can enable P2P energy trading. It also proposes a theoretical model of a blockchain-based P2P energy trading. The paper is structured as follows: Section 2 gives a background on blockchain technology. Section 3 explains the main features of P2P energy trading. Section 4 presents the proposed model of a blockchain-based P2P energy trading. The conclusion summarizes the main findings, contributions, and limitations of the paper and suggests some directions for future research.

2. Blockchain Technology. Blockchain is decentralized Distributed Ledger Technology that stores digital information securely spread across all nodes connected in a peer-to-peer (P2P) network. It contains a continuously expanding record of transactions in their chronological order. In other words, it is a ledger that can contain digital transactions, data records, and executables. The language should be precise and unambiguous to avoid confusion. It is essential to adhere to metrics, units, and standardized language when working with blockchains. Transactions are grouped into larger formations known as blocks, which are time-stamped and cryptographically linked to previous blocks to create a chain of records that establishes the sequence of events or the ‘blockchain’. In addition to describing the data structure, the system assigns a unique identifier to each block. The term is also widely used in literature to describe digital consensus architectures, algorithms, or domains of applications built on such architectures [5, 7].

Some of the characteristics of blockchain include:

- No tampering - The fundamental aspect of blockchain is its immutability. It cannot be modified or tampered with due to its unique ledger, called the ‘blockchain’.

Transactions are added to the chain in chronological order using blocks. The consensus mechanism plays a vital role in ensuring the integrity of the chain. It is highly impractical to make changes to many blocks due to the associated high costs. Consider the blockchain networks such as Bitcoin and Ethereum, which operate using Proof of Work (PoF) consensus mechanism. With just 51% of the computing power, all blocks can be regenerated to tamper with data. However, it is not possible to destroy the data. The needs of players with significant computing power are prioritized through this practical design, which improves the dependability of data on the blockchain.

- Hash functions and cryptography - this revolves around a mathematical function that takes any input and produces a fixed-size output for the specific parameter. This computation converts the information into a bit string format called hash. Such functions possess collision resistance, meaning that no two inputs can lead to the same output. This safety measure allows for retaining the input value, given the extreme difficulty in undoing the outcome and retrieving the original data.

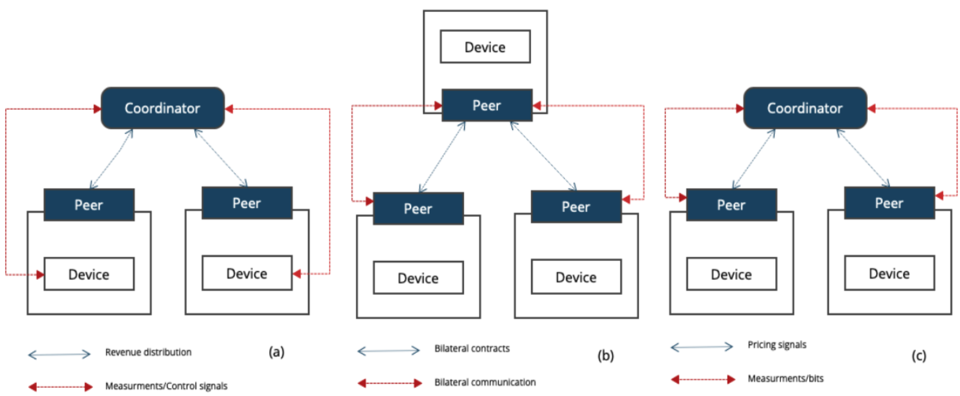
- Smart Contract - Smart contracts are user-defined programs that dictate writing rules in the ledger. They are executable programs, capable of making modifications and triggered automatically when specific conditions, such as an agreement, are met between the transacting parties. Contractual terms are encoded in computer language to ensure legal obligations and conditions are met. Smart contracts are tamper-proof and self-enforcing, providing significant advantages such as eliminating middlemen. This reduces the need for transaction, contracting, enforcement, and communication.

- Decentralization - No third party or central node is involved in validating transactions, reducing costs, and avoiding performance issues. Consensus algorithms ensure consistency and integrity. While different blockchains offer varying degrees of decentralization based on their policies, no node can exert complete control as all nodes maintain the blockchain information.

- P2P network transactions - It is also known as Distributed Ledger Technology (DLT), utilizing a P2P network to secure data through cryptographic functions. The system is transparent and immutable. This approach follows a logical sequence and avoids excessive jargon, maintaining a formal tone and precise word choice. Consistency is maintained throughout, adhering to specific industry standards and metrics. Non-essential fillers have been removed, resulting in a concise and grammatically correct document. This approach facilitates energy transfer between customers.

3. P2P energy trading. P2P energy trading is a groundbreaking approach in the modern power system, enabling users with distributed energy resources (DERs) to exchange energy without a centralized authority. This innovative model offers numerous advantages, such as pollution reduction, cost savings, resource allocation optimization, and support for climate action initiatives. However, it also presents several challenges, including maintaining market stability, coordinating with external markets, and safeguarding user privacy and autonomy. Therefore, the task of designing suitable market arrangements for P2P energy trading is both critical and complex [6, 12].

A central consideration in the market design for P2P energy trading is the degree of centralization. As illustrated in Figure 1, the market can be classified into three types based on the role and function of the coordinator: centralized, decentralized, and distributed. In centralized markets, a coordinator determines the energy transactions and prices for the users, using the information gathered from them. While this market type can optimize the social welfare of the entire P2P community, it demands extensive computation and communication and may infringe on the privacy and autonomy of the users. On the other hand, decentralized markets lack a coordinator, and users trade directly with each other, guided by their individual preferences and strategies. This market type safeguards user privacy and autonomy and offers greater scalability and reliability, but it may also lead to lower efficiency, increased uncertainty, and network congestion. Lastly, distributed markets feature a coordinator who indirectly influences users by transmitting pricing signals, rather than directly controlling their devices or transactions. This market type strikes a balance between user efficiency and privacy and offers improved visibility and predictability of market outcomes for network operators [12]. Despite these potential benefits, implementing blockchain technology in the energy market would require significant regulatory changes and could impact the role of intermediaries, such as brokers, exchanges, and trading agencies. Overcoming significant technical challenges and roadblocks is necessary to realize this vision in practice [2, 8].



4. Blockchain-based P2P energy trading. In peer-to-peer (P2P) energy trading, blockchain technology can be used to execute payment transactions. These transactions, which record the payer, payee, and payment amount, can be initiated and securely logged on a decentralized ledger. This is achieved by using smart contracts, which are pieces of programming code that implement rules for calculating energy payments based on the energy tariff spot price and the energy usage recorded by smart meters. These contracts act as agents that can be triggered at certain points in time, effectively replacing intermediaries or a central authority [5, 11].

A peer-to-peer (P2P) energy trading system using blockchain technology is composed of several integral components. The User Interface (UI), which could be a website or an app, allows users to track their energy usage and manage energy trades. The Smart Meter Interface, an IoT device, communicates with smart meters and initiates transactions when energy sharing begins. Smart contracts on the blockchain are self-executing and contain the terms of the energy tariff and payment calculations. Transaction Processing is a system that verifies transactions and creates blocks of them. The Blockchain Miner validates these blocks and adds them to the blockchain, and then disseminates them to the network. The Blockchain is a distributed ledger that logs all transactions. The Consensus Mechanism is a protocol that ensures network nodes agree on the validity of transactions. Selecting the appropriate consensus mechanism is critical for the system's efficiency, scalability, and security. Proof of Work (PoW), though highly secure, is unsuitable due to its excessive energy consumption, which contradicts the sustainability goals of the energy market. Instead, Proof of Stake (PoS) or Delegated Proof of Stake (DPoS) are more suitable for energy trading systems as they offer significantly lower energy consumption, faster transaction validation, and scalability. Practical Byzantine Fault Tolerance (PBFT) is another option for smaller, localized energy trading networks, providing high throughput and energy efficiency. A hybrid approach combining PoS and PBFT could also be considered, enabling scalability for larger networks while maintaining security and performance for smaller segments. Layer 2 solutions, such as rollups or state channels, can further enhance scalability and reduce on-chain congestion by handling microtransactions off-chain. The Security Module is a cryptographic component that secures transactions. For a critical resource market like energy, robust security measures are essential to protect the system from attacks. Smart contracts should employ advanced cryptographic techniques such as Zero-Knowledge Proofs (ZKPs) to ensure transaction privacy while maintaining transparency. Homomorphic encryption can secure sensitive energy consumption data while allowing computations on encrypted data. Furthermore, a multi-signature protocol can add an additional layer of security, requiring multiple stakeholders to validate critical operations. To prevent Sybil attacks and maintain the integrity of the network, identity verification mechanisms can be implemented, such as public-private key cryptography. The Database stores all transaction data and user information. The API Gateway directs client requests to microservices and manages authentication. Microservices are small, independent services that implement specific business capabilities. Finally, the Message Broker facilitates asynchronous communication between microservices. This architecture enables a decentralized, secure, and transparent system for P2P energy trading.[6]

The transaction processing in a peer-to-peer (P2P) energy trading system involves several steps, as illustrated in Figure 2. Initially, energy sharing commences between prosumers and consumers in a P2P trading manner. As soon as the energy sharing starts, payment transactions are initiated through smart contracts. These smart contracts parse the tariff and energy import/export to calculate the payment price. Following this, the transaction record, which includes the block producers' identification, payer ID, payee ID, and payment amount, becomes part of a list of many transaction records. This list is then encrypted using homomorphic encryption or zero-knowledge proof, forming a block. Subsequently, a blockchain miner validates the block of transactions and produces a candidate block, which is broadcast to all nodes on the network. All network nodes validate the transactions using a consensus mechanism. Miners generally check the corresponding accounts and whether participants have sufficient funds. If they do, the transactions are authenticated and validated by the network. The Merkle tree structure plays a central role in maintaining data provenance within a blockchain by creating a hierarchical structure of hashed data. Each node in the Merkle tree represents a hash of its children, ensuring the integrity of the entire dataset and enabling efficient verification of data consistency and provenance across the decentralized network. This hashed value will keep track of changes in the prosumers Blockchain, making sure that every appending to the data will be caught [1]. Finally, a blockchain is created by linking blocks together through the hash and common block signatures, effectively maintaining a complete list of all past records in a linked list. Additionally, decentralized networks can enhance resilience by distributing nodes across geographic regions, ensuring operational continuity even in case of local outages. Fault-tolerant mechanisms such as automatic failover and checkpointing can prevent data loss during major system disruptions. Distributed storage solutions like IPFS can store historical energy usage data efficiently while reducing reliance on a single point of failure.[4] [3]

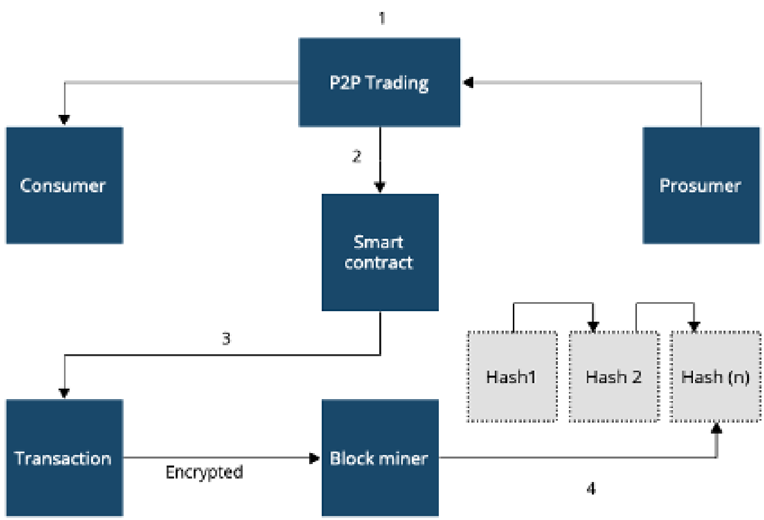


Fig. 2. Adaptation of blockchain-based P2P trading. [11]

This architecture allows for a decentralized, secure, and transparent system for P2P energy trading. It eliminates the need for intermediaries, reduces transaction costs, and enables real-time settlement of energy trades. By addressing critical challenges such as scalability, energy efficiency, security, and resilience, this system ensures a robust and sustainable solution for the future of energy trading.

4. CONCLUSION AND FUTURE DEVELOPMENTS. With the introduction of blockchain technology, the energy sector is undergoing considerable disruption. This decentralized, transparent, and immutable technology has the potential to transform the energy sector, particularly in the context of peer-to-peer (P2P) energy trade. It enables direct interaction between energy providers and customers, democratizing the market and maximizing resource usage. However, the application of blockchain in P2P energy trade is fraught with challenges, including scalability, energy consumption, legal and regulatory frameworks, and user acceptability. To unlock the full potential of blockchain technology in P2P energy trading, future research should focus on addressing these obstacles through innovative solutions. For instance, selecting and optimizing suitable consensus mechanisms such as Proof of Stake or Practical Byzantine Fault Tolerance will be critical to ensure energy efficiency and scalability. Developing robust security protocols, including Zero-Knowledge Proofs, homomorphic encryption, and multi-signature approaches, can enhance resilience and protect this critical resource market from vulnerabilities. Enhancing scalability with Layer 2 technologies, improving energy efficiency with consensus mechanisms like Proof of Stake, and developing frameworks to align blockchain applications with existing energy regulations are critical areas of exploration. Moreover, user-friendly interfaces and educational initiatives will be essential to drive broader adoption and trust in blockchain-based systems.

Finally, to fully realize the promise of blockchain technology in the energy sector, a multi-pronged approach comprising technological innovation, regulatory reform, and active stakeholder engagement is required. Collaborative efforts between governments, energy providers, and technology developers will be essential to building robust frameworks that support blockchain adoption while ensuring environmental sustainability, energy equity, and economic viability. This study provides an overview of the application of blockchain technology in P2P energy trading. The insights on consensus mechanisms and security challenges presented here should serve as a foundation for further investigation into more specialized and technical implementations. Therefore, this work should be viewed as a starting point for understanding the role of blockchain in P2P energy trading, and further research is needed to gain a more comprehensive understanding of this complex field.

References

[1] J. Ackermann, M. Meier. Blockchain 3.0 - The next generation of blockchain systems. Accessed: Dec. 09, 2023. [Online]. Available: `https://www.researchgate.net/publication/327672110_Blockchain_30_-_The_next_generation_of_blockchain_systems`

[2] M. Andoni et al. Blockchain technology in the energy sector: A systematic review of challenges and opportunities, *Renewable and Sustainable Energy Reviews*, vol. 100, pp. 143–174, Feb. 2019, doi: 10.1016/J.RSER.2018.10.014.

[3] C. Fan, H. Khazaei, and P. Musile. BPET: A Unified Blockchain-Based Framework for Peer-to-Peer Energy Trading, *Future Internet*, vol. 16, no. 5, p. 162, May 2024, doi: 10.3390/fi16050162.

[4] A. M. A. Haque, M. M. Hasan, M. S. Hossain. Blockchain, Data Protection and P2P Energy Trading: A Review on European Legal Perspective, *Sustainability*, vol. 14, no. 23, p. 16305, Dec. 2022, doi: 10.3390/su142316305.

[5] Y. Lv. Transitioning to sustainable energy: opportunities, challenges, and the potential of blockchain technology, *Frontiers in Energy Research*, vol. 11, Sep. 2023, doi: 10.3389/fenrg.2023.1258044.

[6] P. Maya, P. A. Salam. A review of peer-to-peer transaction loss and blockchain: challenges and drivers in the roadmap to a low-carbon future, *Frontiers in Energy Research*, vol. 12, Jul. 2024, doi: 10.3389/fenrg.2024.1397975.

[7] S. Peng. Blockchain for big data AI, IoT and Cloud perspectives, 1st Edition. CRC Press, 2022.
[8] M. K. Thukral. Emergence of blockchain-technology application in peer-to-peer electrical-energy trading: a review, *Clean Energy*, vol. 5, no. 1, pp. 104–123, Mar. 2021, doi: 10.1093/ce/zkaa033.
[9] M. Walport (ed). Distributed ledger technology: beyond block chain - GOV.UK. Accessed: Nov. 04, 2023. [Online]. Available: https://www.gov.uk/government/news/distributed-ledger-technology-beyond-block-chain.
[10] Q. Wang, M. Su. Integrating blockchain technology into the energy sector — from theory of blockchain to research and application of energy blockchain, *Comput Sci Rev*, vol. 37, p. 100275, Aug. 2020, doi: 10.1016/J.COSREV.2020.100275.
[11] P. Wongthongtham, D. Marrable, B. Abu-Salih, X. Liu, G. Morrison. Blockchain-enabled Peer-to-Peer energy trading, *Computers & Electrical Engineering*, vol. 94, p. 107299, Sep. 2021, doi:10.1016/J.COMPELECENG.2021.107299.
[12] Y. Zhou, J. Wu, C. Long, W. Ming. State-of-the-Art Analysis and Perspectives for Peer-to-Peer Energy Trading, *Engineering*, vol. 6, no. 7, pp. 739–753, Jul. 2020, doi: 10.1016/J.ENG.2020.06.002.