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Blockchain-Based Fully Peer-to-Peer Energy Trading Platform for Residential Energy Systems

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Abstract - *The rapid growth of renewable energy resources has increased the participation of residential users as both energy producers and consumers. However, traditional energy trading systems rely on centralized intermediaries, leading to reduced transparency, higher operational costs, and limited flexibility for small-scale energy producers. This paper proposes a blockchain-based fully peer-to-peer energy trading platform designed for residential energy systems. The proposed system enables direct energy trading between users without the involvement of third-party intermediaries by leveraging the decentralized nature of blockchain technology. Energy units are represented as digital tokens using the ERC-20 standard, and smart contracts are deployed on the Ethereum Sepolia test network to automate listing creation, pricing, transaction execution, and settlement. A web-based interface integrated with a backend service allows users to interact with the blockchain securely through wallet authentication. This ensures transparency, immutability, and trust by recording all transactions on the blockchain while maintaining performance through off-chain data management. Experimental evaluation demonstrates the feasibility of the proposed platform in terms of transaction execution, gas cost efficiency, and system reliability. The results indicate that blockchain-based peer-to-peer energy trading can serve as an effective solution for decentralized residential energy markets, with potential scalability for future smart grid integration.*

Key Words: **Blockchain, Peer-to-Peer Energy Trading, Smart Contracts, Ethereum, Renewable Energy, ERC-20 Token, Decentralized Applications.**

1. INTRODUCTION

The global energy sector is undergoing a significant transformation due to the rapid adoption of renewable energy resources such as solar and wind power. Advances in distributed generation technologies have enabled residential users to generate their own electricity, leading to the emergence of prosumers who can both produce and consume energy. While this shift promotes sustainability, it also introduces new challenges related to energy distribution, pricing, and management within traditional power systems.

Conventional energy trading mechanisms are predominantly centralized and controlled by utility providers or third-party intermediaries. These centralized systems often lack transparency, involve high operational costs, and provide limited flexibility for small-scale energy producers. Moreover, centralized control introduces single points of failure and reduces user trust in pricing and settlement processes. As a result, there is a growing need for decentralized solutions that allow direct energy trading among residential users in a secure and transparent manner.

Blockchain technology has emerged as a promising solution to address these challenges. As a decentralized and immutable ledger, blockchain enables trustless transactions without relying on centralized authorities. Through the use of smart contracts, blockchain systems can automate transaction execution, enforce predefined rules, and ensure tamper-proof record keeping. These features make blockchain an ideal platform for implementing peer-to-peer energy trading systems that emphasize transparency, security, and efficiency.

This paper proposes a blockchain-based fully peer-to-peer energy trading platform designed specifically for residential energy systems. The proposed system allows users to trade surplus energy directly with other users using digital energy tokens. Smart contracts deployed on the Ethereum blockchain automate the entire trading workflow, including energy listing creation, pricing, transaction validation, and settlement. By eliminating intermediaries, the platform reduces operational overhead and empowers residential prosumers to actively participate in energy markets.

1.1 Blockchain-Based Peer-to-Peer Energy Trading

Peer-to-peer energy trading refers to a decentralized model in which energy producers and consumers interact directly without centralized control. In residential environments, this model enables households with surplus energy generation to sell excess energy to neighbouring consumers at mutually agreed prices. Blockchain technology plays a critical role in enabling this decentralized approach by providing a secure, transparent, and distributed transaction infrastructure.

In blockchain-based energy trading systems, smart contracts act as autonomous agents that manage trading logic. These contracts automatically execute transactions when predefined conditions are met, ensuring fairness and eliminating manual intervention. Additionally, blockchain records all transactions in an immutable ledger, allowing

participants to verify trading history and preventing fraudulent activities.

In the proposed system, energy units are tokenized using the ERC-20 standard, where each token represents a fixed quantity of energy. Tokenization enables energy to be treated as a tradable digital asset that can be transferred securely between users. This approach simplifies accounting, improves interoperability, and enhances scalability. By combining tokenization with smart contracts, the system ensures that energy trading remains transparent, secure, and efficient.

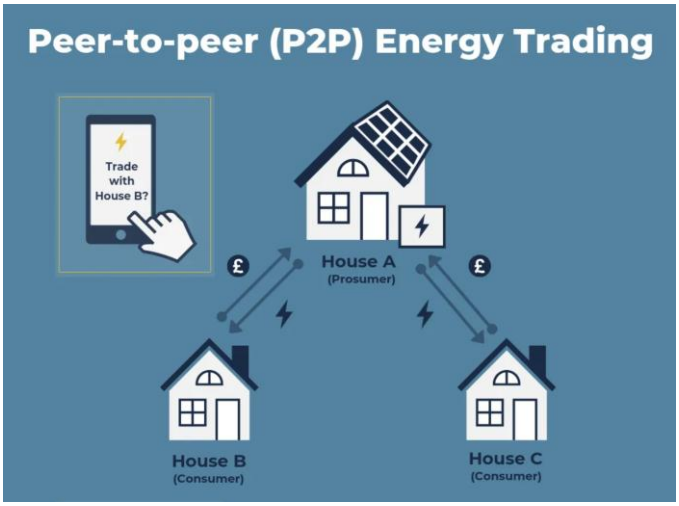

Fig -1: Conceptual overview of blockchain-based peer-to-peer energy trading between residential prosumers and consumers

1.2 Motivation and Problem Overview

Peer-to-peer energy trading refers to a decentralized model in which energy producers and consumers interact directly without centralized control. In residential environments, this model enables households with surplus energy generation to sell excess energy to neigh boring consumers at mutually agreed prices. Blockchain technology plays a critical role in enabling this decentralized approach by providing a secure, transparent, and distributed transaction infrastructure.

Despite the increasing adoption of renewable energy technologies, existing energy trading infrastructures are not designed to support decentralized participation effectively. Traditional systems rely on centralized intermediaries for energy pricing, transaction settlement, and data management. These intermediaries increase transaction costs, delay settlement processes, and reduce transparency for end users.

Another major limitation of centralized energy trading systems is their inability to scale efficiently with the growing number of residential energy producers. As the number of prosumers increases, centralized systems become complex to manage and prone to inefficiencies. Furthermore, centralized control restricts innovation and prevents users from actively participating in local energy markets.

The motivation behind this work is to design a decentralized platform that overcomes these limitations by leveraging blockchain technology. The proposed system enables transparent energy pricing, automated settlement, and direct interaction between producers and consumers. By decentralizing energy trading, the platform reduces dependency on intermediaries and supports fair participation for all users.

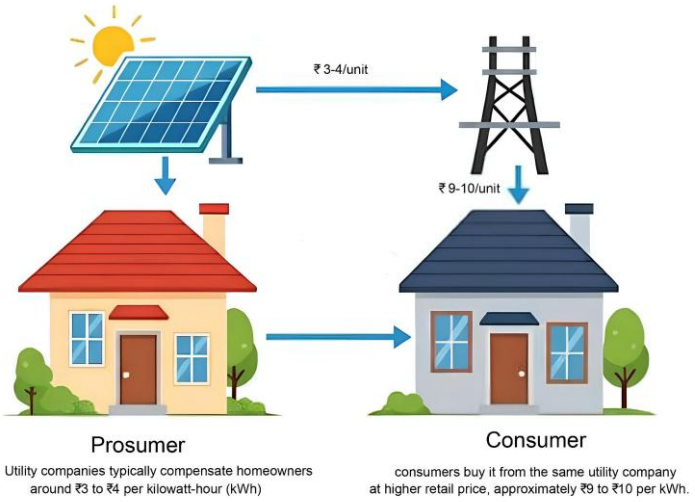

Fig -2: Comparison between traditional grid-based energy trading and prosumer–consumer pricing

2. PROPOSED SYSTEM

The proposed system presents a blockchain-based fully peer-to-peer (P2P) energy trading platform that enables direct energy transactions between residential prosumers and consumers without the involvement of centralized utility providers. The system leverages blockchain technology to ensure transparency, security, and immutability of energy transactions while reducing energy costs and improving trust among participants.

In this model, residential users equipped with renewable energy sources such as solar panels can act as prosumers, generating surplus energy beyond their consumption needs. This surplus energy is tokenized and traded directly with nearby consumers through smart contracts deployed on a blockchain network. By eliminating intermediaries, the proposed system ensures fair pricing, faster settlement, and decentralized control.

The overall architecture integrates a web-based user interface, blockchain smart contracts, and a backend server to manage off-chain data and system coordination. Users interact with the platform using blockchain wallets, ensuring secure authentication and authorization for all transactions.

2.1 System Architecture

The system architecture consists of four major components: the frontend interface, backend services, blockchain layer, and database layer. Each component plays a crucial role in enabling seamless peer-to-peer energy trading.

The frontend is developed using a web-based framework and provides an intuitive user interface for buyers and sellers to view energy listings, connect wallets, and initiate transactions. User authentication is performed using a blockchain wallet such as MetaMask, which allows users to sign transactions securely without exposing private keys.

The backend is implemented using Node.js and Express.js, acting as an intermediary between the frontend and the blockchain network. It handles business logic, user management, listing management, and transaction synchronization. RESTful APIs are used to communicate between the frontend and backend.

The blockchain layer is built on the Ethereum Sepolia test network. Two smart contracts are deployed on the blockchain: an ERC-20 compliant Energy Token contract and an Energy Marketplace smart contract. These contracts manage energy token creation, listing, purchase, and settlement in a decentralized manner.

The database layer uses MongoDB to store off-chain data such as user profiles, transaction history, energy listings, and analytics. This hybrid on-chain and off-chain design improves performance while maintaining blockchain integrity.

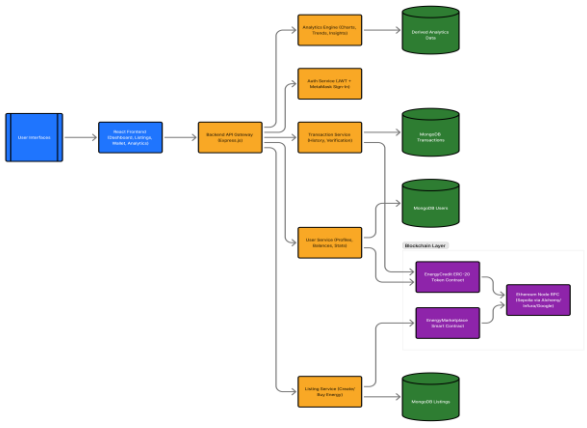

Fig -3: System architecture of the blockchain-based peer-to-peer energy trading platform

2.2 Smart Contract Design

Smart contracts form the core of the proposed system. The Energy Token smart contract follows the ERC-20 standard and represents energy units generated by prosumers. Each token corresponds to a fixed amount of energy and can be transferred securely between blockchain addresses.

The Energy Marketplace smart contract manages the lifecycle of energy trading. Prosumers can create energy listings by specifying the amount of energy tokens and price per unit. Consumers can browse available listings and purchase energy by executing blockchain transactions. Upon successful purchase, tokens are transferred from the seller to the buyer, and the payment is settled automatically.

All transactions are recorded on the blockchain, ensuring transparency and tamper-proof records. Events emitted by smart contracts are monitored by backend event listeners to update the system state in real time.

2.3 Transaction Workflow

The transaction process begins when a consumer selects an energy listing from the platform. The consumer connects their blockchain wallet and signs the transaction using MetaMask. Once signed, the transaction is submitted to the Ethereum network.

The marketplace smart contract verifies the transaction, transfers the required energy tokens, and records the transaction details. An event is emitted upon successful execution, which is captured by the backend event listener. The backend then updates the database with transaction status and reflects the updated balances in the user interface.

This automated workflow eliminates manual intervention, reduces transaction delays, and ensures trustless execution of energy trades.

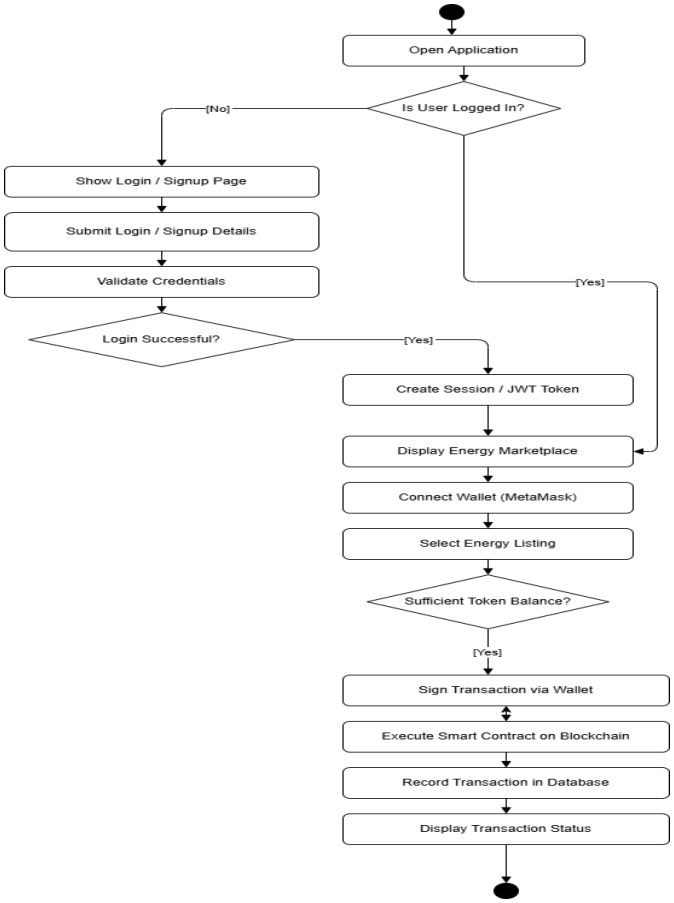

Fig -4: Transaction workflow of the proposed peer-to-peer energy trading system

3. IMPLEMENTATION DETAILS

The implementation of the proposed blockchain-based peer-to-peer energy trading platform is carried out using a combination of blockchain technology, web-based application frameworks, and database systems. The implementation is divided into four main layers: blockchain layer, backend layer, frontend layer, and database layer. This layered approach ensures modularity, scalability, and ease of maintenance.

3.1Blockchain Layer Implementation

The blockchain layer is implemented using the Ethereum blockchain, specifically the Sepolia test network, to avoid real-world financial risks during development and testing. Smart contracts are developed using the Solidity programming language and deployed using development tools such as Hardhat.

The Energy Token smart contract follows the ERC-20 standard and represents energy units generated by prosumers. Each token corresponds to a predefined quantity of energy. The contract includes standard ERC-20 functionalities such as token transfer, balance checking, and allowance mechanisms.

This contract ensures secure and transparent token management, allowing energy units to be traded seamlessly between buyers and sellers. The immutability of the blockchain ensures that token balances cannot be tampered with.

3.2Backend Layer Implementation

The backend layer is implemented using Node.js and Express.js. It serves as a middleware between the frontend application and the blockchain network. The backend performs several critical functions, including user management, energy listing management, transaction synchronization, and analytics.

RESTful APIs are developed to handle operations such as creating listings, fetching transaction history, verifying blockchain transactions, and updating system state. The backend also includes an event listener service that continuously monitors blockchain events emitted by the smart contracts.

Upon detecting a blockchain event, the backend validates the transaction and stores the corresponding data in the database. This hybrid approach ensures both blockchain integrity and system efficiency.

3.3Frontend Layer Implementation

The frontend layer is developed using a web-based framework and provides an interactive user interface for system users. The interface allows users to register, log in, view available energy listings, and initiate energy purchase transactions.

Blockchain wallet integration is achieved using MetaMask, which enables users to connect their wallets and sign transactions securely. No private keys are stored on the server, ensuring high security and user privacy.

The frontend communicates with the backend through secure APIs and directly interacts with smart contracts via the wallet provider. Real-time transaction status updates are displayed to users after blockchain confirmation.

3.4 Database Layer Implementation

The database layer is implemented using MongoDB, a NoSQL database suitable for handling large volumes of unstructured and semi-structured data. The database stores off-chain data such as user profiles, transaction records, energy listings, and system logs.

Blockchain transaction hashes are stored alongside database records to ensure traceability and verification. This combination of on-chain and off-chain storage improves system performance while maintaining transparency.

3.5 Security Considerations

Security is a critical aspect of the system implementation. Blockchain-based authentication ensures that only authorized users can initiate transactions. Smart contracts are designed to prevent unauthorized access and double spending.

Additionally, backend validation and secure API communication protect the system from common web vulnerabilities. The use of blockchain wallets eliminates the need for password-based authentication, reducing the risk of credential theft.

4. RESULTS AND PERFORMANCE ANALYSIS

This section discusses the results obtained after implementing and testing the proposed blockchain-based peer-to-peer energy trading platform. The system was evaluated in a controlled test environment using the Ethereum Sepolia test network to simulate real-world energy trading scenarios.

Several test cases were conducted to verify the correctness of smart contract execution, token transfers, and transaction settlement. Prosumers were able to successfully create energy listings, and consumers were able to browse and purchase available energy units through the platform.

4.1 Transaction Execution and Validation

Each energy purchase transaction was executed through the Energy Marketplace smart contract. Upon execution, the smart contract validated token availability, transferred energy tokens from seller to buyer, and completed payment settlement. All transactions were confirmed on the blockchain, ensuring transparency and immutability.

Blockchain transaction hashes generated during the execution were stored in the database for verification and auditing purposes. This ensured traceability of every energy trade performed through the platform.

In order to validate the correctness of energy trading operations, multiple transaction scenarios were executed on the Ethereum Sepolia test network. These scenarios included successful purchases, insufficient balance cases, and invalid transaction attempts. The smart contracts correctly enforced predefined rules such as balance verification, listing availability, and ownership checks before allowing transaction execution. Once validated, each transaction was confirmed on the blockchain and assigned a unique transaction hash, ensuring traceability and preventing tampering. This confirms the reliability of smart contract–based execution for decentralized energy trading.

4.2 Performance Analysis

The performance of the system was evaluated based on transaction latency, system reliability, and scalability. The average transaction confirmation time depended on the blockchain network conditions and was found to be acceptable for peer-to-peer energy trading scenarios.

The hybrid architecture combining on-chain and off-chain components significantly reduced system overhead. While critical transaction data was stored on the blockchain, non-critical data such as user profiles and analytics were handled off-chain, improving overall system efficiency.

Performance evaluation focused on transaction confirmation time, system responsiveness, and backend synchronization. The observed transaction latency primarily depended on blockchain network conditions and block confirmation time. Despite this dependency, the user interface remained responsive due to asynchronous transaction handling and backend event listeners. The separation of on-chain and off-chain operations minimized performance bottlenecks, demonstrating that the system can handle real-time user interactions efficiently in residential-scale deployments.

4.3 Cost Analysis

The transaction process begins when a consumer selects an energy listing from the platform. The consumer connects their blockchain wallet and signs the transaction using MetaMask. Once signed, the transaction is submitted to the Ethereum network.

The cost analysis highlights the economic benefits of eliminating centralized intermediaries in energy trading. By enabling direct peer-to-peer transactions, the proposed system reduces additional charges typically imposed by utility providers and third-party platforms. While blockchain-based transactions involve gas fees, these costs are predictable and can be optimized through efficient smart contract design. The overall cost structure favours both prosumers and consumers, making the system suitable for decentralized energy marketplaces with transparent pricing models.

Using a blockchain-based marketplace eliminated the need for centralized intermediaries, thereby reducing energy trading costs. Prosumers received fair compensation for surplus energy, while consumers benefited from lower energy prices compared to traditional grid-based systems.

The use of a test network during implementation demonstrated that the system can be deployed on a production block chain with minimal modifications.

5. CONCLUSIONS

The proposed blockchain-based fully peer-to-peer energy trading platform demonstrates an effective solution for decentralized residential energy exchange. By leveraging Ethereum smart contracts and ERC-20 energy tokens, the system enables secure, transparent, and trustless energy trading between prosumers and consumers without relying on centralized intermediaries.

The implementation validates that blockchain technology can significantly reduce transaction overhead, improve energy price fairness, and enhance transparency in energy markets. The integration of a web-based interface with smart contract execution ensures usability while maintaining the benefits of decentralization.

Overall, the proposed system proves to be a viable and scalable approach for future decentralized energy marketplaces and supports the increasing adoption of renewable energy resources.

6. FUTURE WORK

Although the current implementation successfully demonstrates peer-to-peer energy trading, several enhancements can be considered in future work. Integration with real-time smart meters can enable automated energy measurement and settlement. Dynamic pricing models based on demand and supply conditions can further optimize trading efficiency.

Additionally, deploying the system on a high-throughput blockchain or Layer-2 solution can improve scalability and reduce transaction costs. Future research may also explore the use of artificial intelligence for energy demand forecasting and grid optimization.

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