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A MODEL FOR SAFEGUARDING SECURITY AND PRIVACY IN PEER-TO-PEER ENERGY TRADING

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Abstract

Peer-to-peer (P2P) energy trading has emerged as a decentralized approach that enables prosumers to sell surplus electricity directly to consumers, bypassing intermediaries and fostering affordability and efficiency. However, the widespread adoption of P2P systems is hindered by critical challenges of security, privacy, trust, and regulatory uncertainty. This study aims to develop a blockchain-based model that safeguards security and privacy in P2P energy trading. The objectives include analyzing cyber

Keywords: Blockchain, Peer-to-Peer (P2P) Energy Trading, Cybersecurity, Privacy Preservation, Smart Contracts, Renewable Energy, Adamawa State.

INTRODUCTION

Peer-to-peer (P2P) trading of energy has emerged as a next-generation system in energy management that enables prosumers to trade their surplus electricity. This model allows transactions on both private and community-owned energy generators and storage sites to sell their energy directly to consumers, eliminating the middleman and providing a cheaper and fairer energy price to the consumer.

Traditionally, electricity trading has operated in centralized systems where generation, transmission, and distribution were monopolized by utilities. This structure relied on large-scale power plants supplying electricity to end-users through hierarchical grids. Centralized electricity systems were initially designed to prioritize reliability and cost-efficiency, leveraging economies of scale to serve industrial, commercial, and residential customers (Joskow, 2020).

threats and data breaches, exploring blockchain's role in enhancing transparency and trust, proposing privacy-preserving mechanisms, and evaluating the model using the Sepolia testnet. A mixed-methods methodology comprising literature review, stakeholder engagement, and system modeling was employed, focusing on Adamawa State, Nigeria. The proposed model integrates blockchain, cryptography, and role-based access to ensure secure authentication, encrypted transactions, and privacy-preserving data exchange. Findings reveal that the model enhances trust, reduces vulnerabilities to cyber threats, and improves operational efficiency compared to centralized systems. It also highlights the importance of localized regulatory frameworks to support adoption in developing nations. The study concludes that blockchain-enabled P2P trading can transform energy distribution if backed by robust policies, privacy mechanisms, and scalability measures, and recommends integration with smart grids and regulatory reforms for large-scale deployment.

Over time, technological advancements and market liberalization prompted a shift towards deregulated electricity markets, introducing competition in generation and retail. While deregulation aimed to improve service delivery, reduce costs, and foster innovation, centralized models still faced challenges, such as vulnerability to large-scale outages and difficulties in adapting to decentralized energy generation (Cali & Fifield, 2019).

Energy trading is managed either using a centralized approach or in a decentralized and distributed manner. In the centralized approach, an intermediary entity single-handedly manages, processes, and validates transactions between different users. However, this approach increases the risks of a single point of failure and the overall cost of the system. Furthermore, security and privacy-related problems are also part of the centralized approach's drawbacks. A significant electricity failure in the system may be disastrous for consumers if an alternate source of energy solution is unreachable. Therefore, distributed and decentralized energy systems are presented as an alternative method to the centralized approach (Shahid *et al*., 2020).

Smart grids are currently advancing technologically at a very fast pace by leveraging the benefits offered by Wireless Sensor Networks (WSNs) and the Internet of Things (IoT). They offer optimization in energy production and consumption by the adoption of intelligent systems that can monitor and communicate with each other. Automation of the smart sensor-based metering system by using Advanced Metering Infrastructure (AMI) leads to a lesser requirement of manpower and more accuracy. Thus, by making the grid more intelligent, efficient energy utilization is achieved (Alladi *et al*., 2019).

The rationale of this study is to address the limitations of the traditional centralized energy trading system and explore the potential of blockchain-based peer-to-peer (P2P) energy trading as a solution. The decentralized and distributed nature of blockchain technology can provide a secure, transparent, and efficient platform for energy transactions, empowering prosumers to actively participate in the energy market and trade their surplus electricity directly with consumers.

Statement of the Problem

Despite the growing recognition of peer-to-peer (P2P) energy trading systems as a promising approach for decentralized energy distribution, serious security and privacy vulnerabilities continue to threaten the widespread adoption and trust in such systems. Numerous researchers, including Jain *et al*. (2013) and Chen *et al*. (2015), have acknowledged the challenges associated with traditional and software-defined networks in managing scalability, control, and trust within distributed environments. These challenges are further amplified in P2P energy trading models, which rely on the seamless exchange of energy and data between multiple, often anonymous, participants. Several studies (e.g., Cao *et al*., 2017; Sanjay, 2018) have emphasized that while Software Defined Networking (SDN) and Software Defined Wide Area Networks (SD-WAN) offer centralized control and programmability, they still suffer from weak endpoint authentication, data tampering risks, and limited protection against insider threats — problems that become critical in energy trading environments where financial transactions and energy flows are directly impacted. Moreover, the reviewed work of Li (2020), Nikmah *et al*. (2021), and Tornatzky & Fleischer (1990) using the Technology-Organization-Environment (TOE) framework identified that technological barriers, such as insufficient encryption and identity protection, organizational weaknesses like lack of technical expertise, and environmental factors including lack of regulatory clarity, continue to undermine the confidence of users and stakeholders in adopting secure peer-to-peer energy systems.

While some researchers have proposed using blockchain and smart contracts to address these issues, the lack of a unified security and privacy model that integrates these technologies with SDN/SD-WAN, trust management, and robust authentication protocols remains a major gap.

Therefore, the problem this study addresses is the absence of a comprehensive and scalable model that safeguards both the security and privacy of participants in P2P energy trading networks, particularly one that aligns with emerging network paradigms and organizational adoption models. Without addressing these challenges holistically, P2P energy trading systems may fail to achieve their potential as secure, trusted alternatives to centralized energy markets.

Aim and Objectives of the Study

The aim of this study is to develop a secure and privacy-preserving blockchain-based model for P2P electricity trading.

The specific objectives are:

i. To analyze the challenges of cyber threats, data breaches, and transaction tampering in P2P systems.
ii. To explore the role of blockchain technology in enhancing transparency, security, and trust in P2P electricity trading.

Scope of the Study

This study focuses on the design of a secure and privacy-preserving peer-to-peer energy trading model using blockchain and SDN technologies. The scope is limited to Yola South Local Government Area of Adamawa State, with an emphasis on resolving security and privacy issues. The study would take into account case studies and use cases from Nigeria and other nations to give a global viewpoint.

Peer-to-Peer Energy Trading

P2P energy trading allows prosumers (grid-connected consumers with generation, e.g., rooftop solar) to sell excess power directly to other consumers. Hamdan et al. (2022) note that P2P trading "enables prosumers to actively participate in the electricity market, and gain incentivized profits." Typically, these trades occur within a microgrid or a cluster of neighboring microgrids, using a platform that matches supply and demand (the business layer) on a peer basis. As illustrated by Hamdan et al. (2022), P2P market architectures often have multiple layers: a power grid layer (physical network and DERs), an ICT layer (communication/network infrastructure), a control layer (hardware/software control of devices), and a business layer (market mechanisms and billing). In practice, several pilots worldwide (e.g., Piclo in the UK, Transactive Grid in the US) have explored this model (Hamdan et al., 2022).

Additionally, Figure 1 shows the typical flow of energy and transactions in a P2P electricity trading system compared to traditional centralized systems.

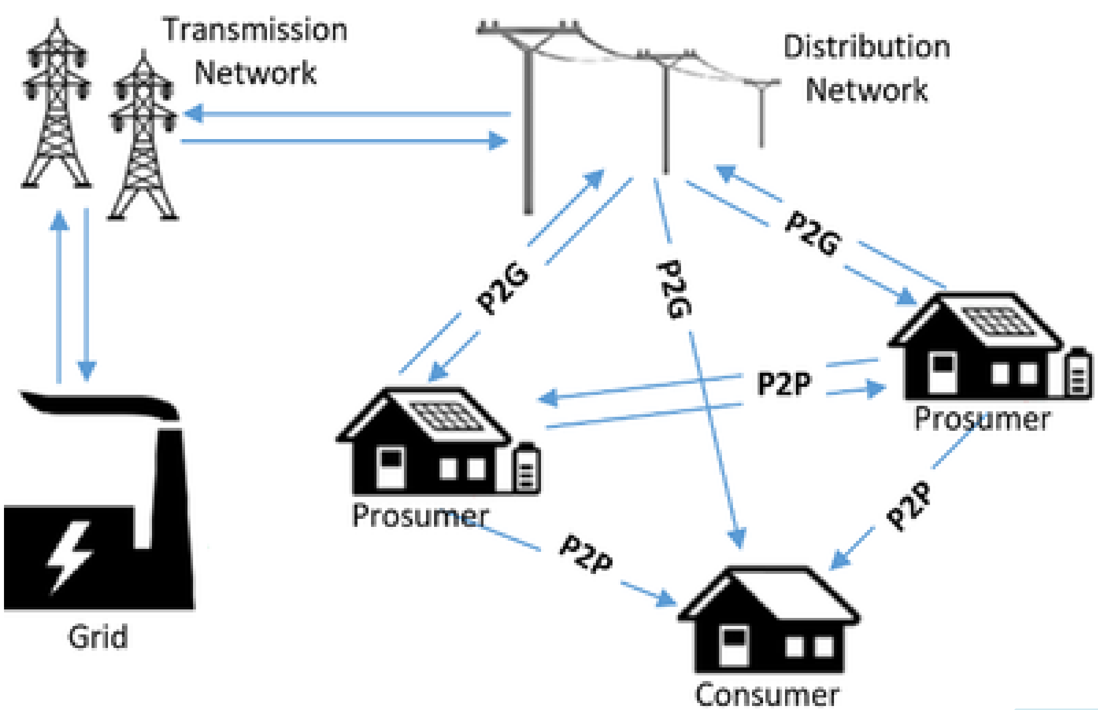


Figure 1: P2P Electricity Trading vs. Centralized Energy Distribution Models (Luthra *et al.* 2022)

In Nigeria, where over 85 million people lack access to electricity (World Bank, 2023), P2P trading presents a viable alternative to extend energy access to underserved regions. Studies by Adebayo *et al.* (2022) highlight that implementing P2P trading platforms in Nigerian rural areas has the potential to reduce reliance on diesel generators, which account for 40% of household energy needs. The adoption of this model aligns with global efforts to transition to decentralized renewable energy systems (Parag & Sovacool, 2020).

Blockchain Technology

Blockchain technology serves as the backbone for P2P electricity trading systems, providing a transparent, immutable, and decentralized ledger for recording transactions. Research by Tapscott and Tapscott (2020) underscores blockchain's ability to eliminate inefficiencies in traditional energy trading systems by enabling real-time settlement of transactions. Blockchain's role in supporting smart contracts, as shown in Figure 2, automates the execution of energy trades, ensuring compliance with predefined conditions such as pricing and delivery schedules.

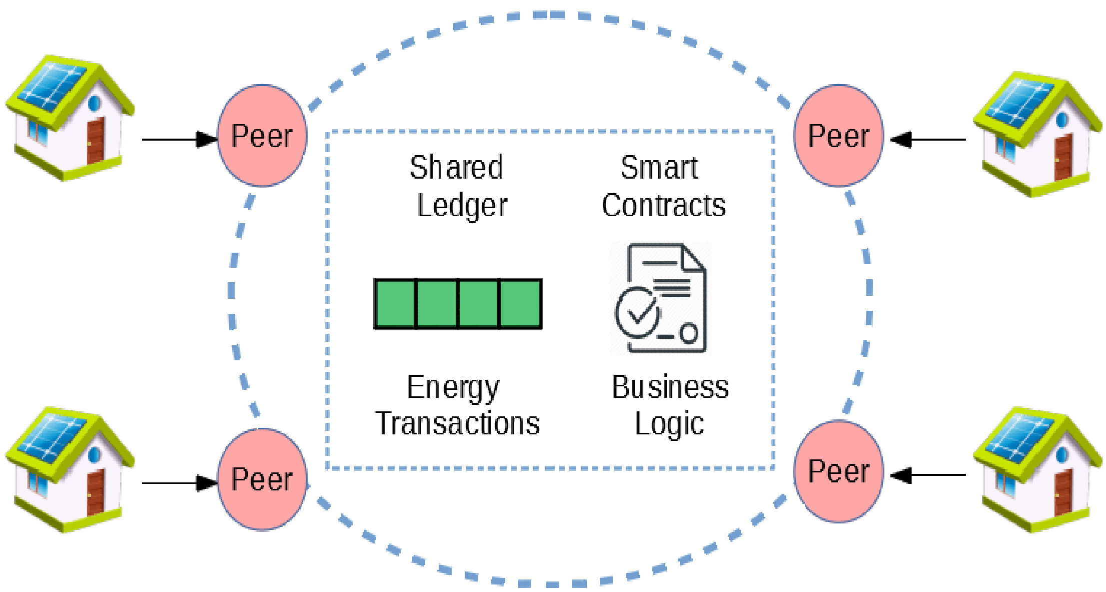


Figure 2: Blockchain-Enabled Smart Contracts in P2P Energy Trading (Tapscott, 2020)

In Nigeria, blockchain adoption is gaining momentum as a tool to address challenges in the energy sector, such as energy theft and billing discrepancies. Okafor *et al.* (2023) reported that blockchain could enhance billing accuracy by up to 35% in Nigerian energy markets, fostering trust between consumers and suppliers.

Security and Privacy

Although public key cryptography could be applied to provide a certain level of security and integrity of information in decentralized systems, integrating blockchain, multisignature approach and anonymous encrypted message will address privacy concerns as well as enable transaction security within a decentralized system (Aitzhan & Svetinovic, 2016).

In the context of Nigeria, cybersecurity threats remain a significant barrier to the adoption of digital platforms. Olayemi & Adeoye (2023) noted that over 60% of Nigerian businesses experienced cyberattacks in 2022, underscoring the need for enhanced security measures in blockchain systems. Privacy-preserving mechanisms, such as differential privacy, are essential to protect user identities and transaction histories, fostering trust among participants in decentralized markets.

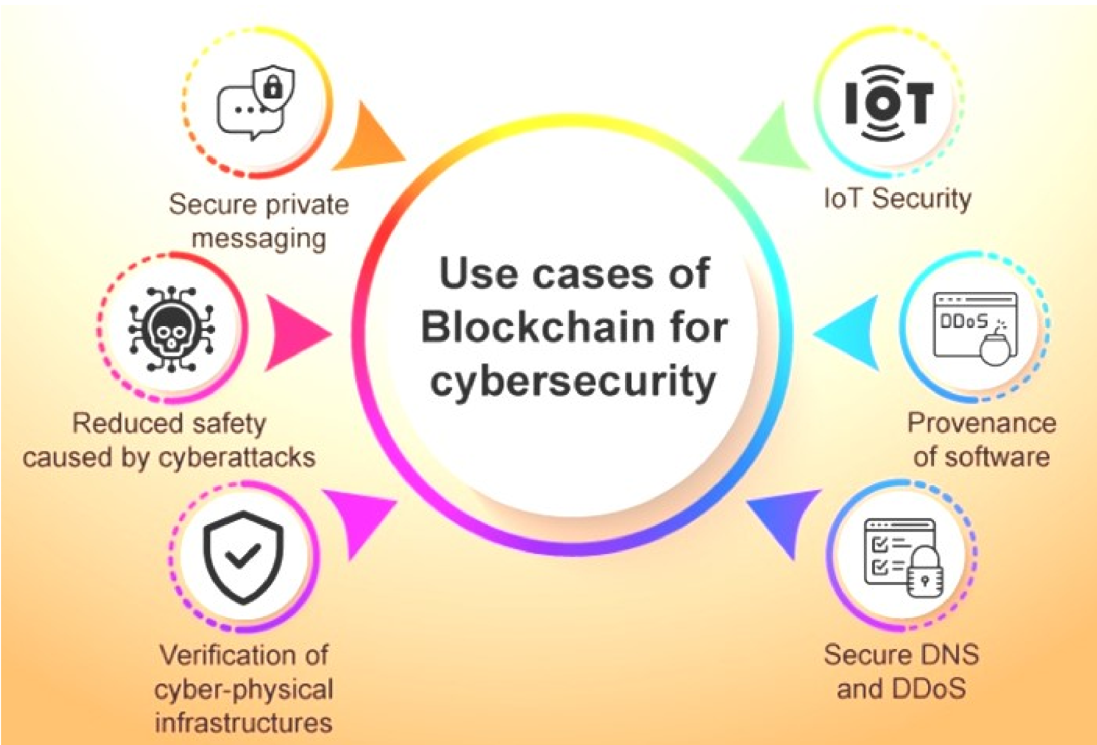


Figure 3: Cybersecurity Solutions for Blockchain-Based Energy Platforms (Adeoye, 2023)

Regulatory Frameworks

Regulatory frameworks play a important role in shaping the adoption and operation of blockchain-based P2P electricity trading systems. In Nigeria, a lack of clear policies has hindered the scalability of decentralized energy platforms. Adebayo *et al*. (2022) emphasized the need for regulatory reforms to standardize energy pricing, data protection, and dispute resolution mechanisms in blockchain-based systems.

Globally, countries like Estonia and Germany have established robust legal frameworks for P2P electricity trading, enabling greater consumer participation and innovation (Newbery, 2021).

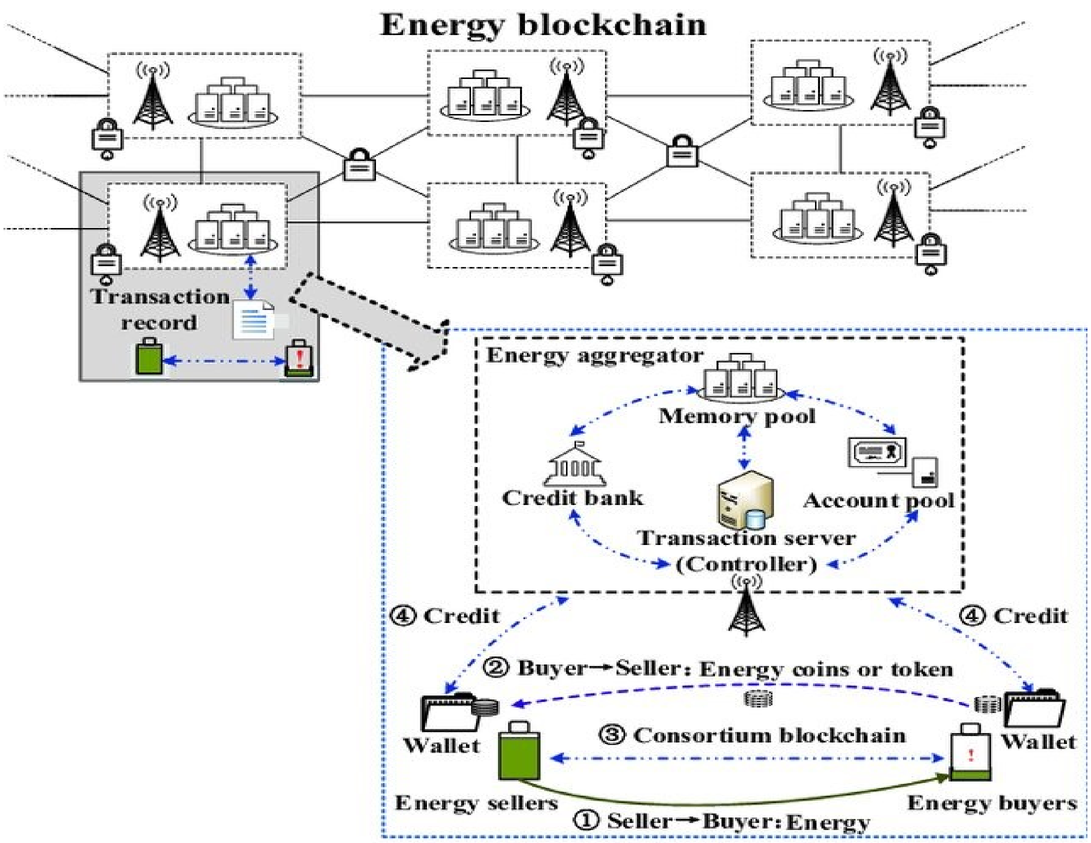


Figure 4: Regulatory Considerations for Blockchain-Based Energy Trading Systems (Newbery, 2021).

Role of Blockchain in P2P Electricity Trading

Blockchain technology serves as a cornerstone for secure and transparent P2P electricity trading systems. Its decentralized nature ensures that all transactions are recorded immutably on a distributed ledger, reducing risks of fraud and data manipulation (Nakamoto, 2020). Smart contracts, an integral feature of blockchain, automate transaction processes, enabling real-time energy exchanges and ensuring fair pricing.

In P2P trading, blockchain addresses critical challenges such as trust, data integrity, and transaction transparency. By decentralizing control, it eliminates the need for intermediaries, reducing operational costs and enhancing efficiency. Nigerian studies highlight blockchain's role in combating energy theft a pervasive issue in the country by ensuring accurate energy metering and billing (Okafor *et al.*, 2023).

Globally, blockchain has been successfully implemented in countries like Australia and Germany, where it enhances grid resilience and consumer trust. According to Aitzhan & svetinovic (2016) P2P networks provides increased security and resilience, although message redundancy and lack of routing might lead to scalability issues. Figure 5, depicts the architecture of a blockchain-based P2P energy trading platform, showcasing its key components

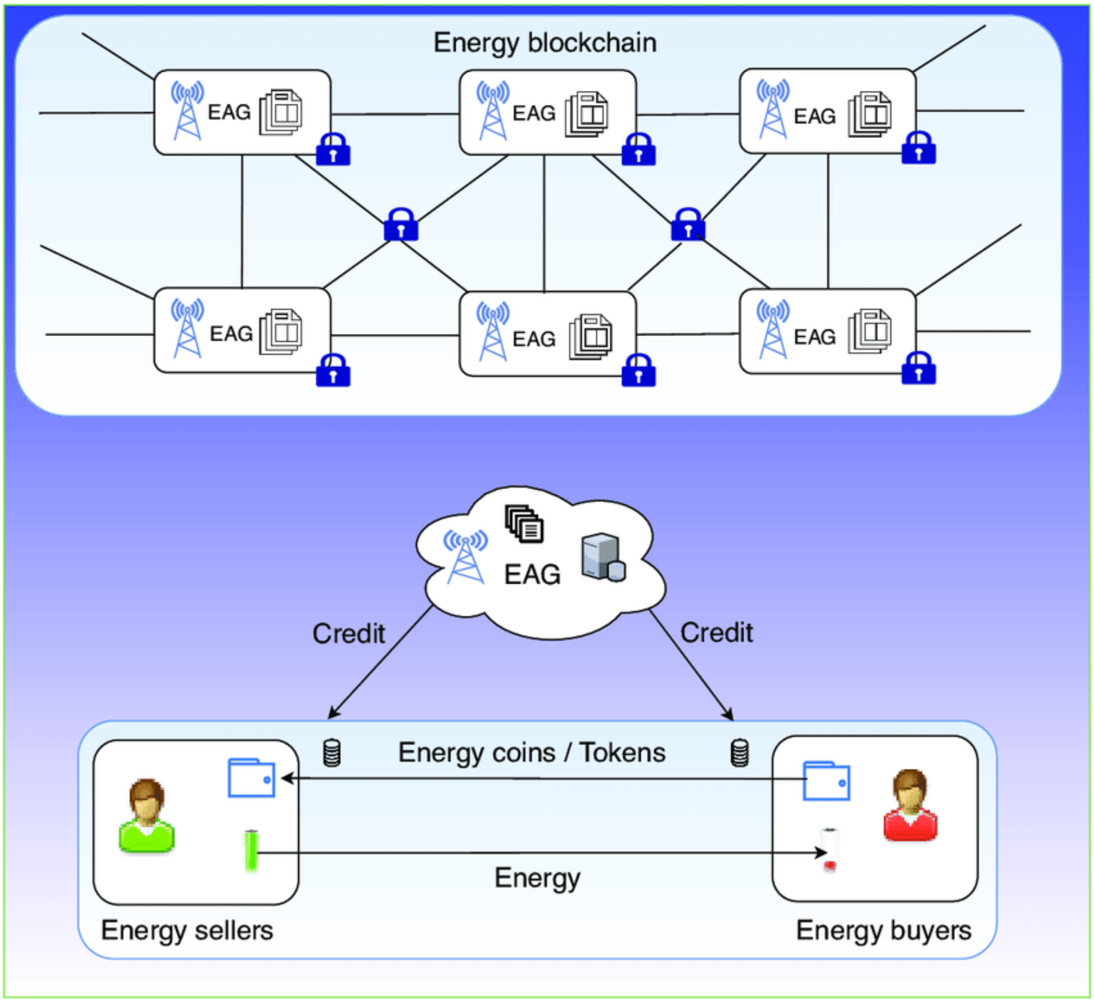


Figure 5: Blockchain-Based P2P Energy Trading Architecture Adapted from (Alladi *et al.* 2019)

In Nigeria, blockchain's adoption in the energy sector is still nascent but promising. Collaborative efforts between policymakers, technology providers, and energy stakeholders are essential to scale its implementation and address operational challenges.

Security and Privacy in Blockchain-Based P2P Systems

The potential benefits of blockchain adoption for smart grids include decentralized peer-to-peer (P2P) energy trading without the need of a third-party intermediary and implementation of secured energy transactions and increased share of distributed renewable energy within the energy grid (Aitzhan & Svetinovic, 2016).

As traditional energy transition to decentralized modern smart grids with the integration of energy internet of things (IoT), cybersecurity is often an afterthought as vendors and end users prioritize functionality and cost, leaving the power grid potentially vulnerable to cyber-attack. Blockchain based smart energy contracts can fill these optimization and security gaps and improve the state of the art in grid resilience by providing an atomically verifiable cryptographic signed distributed ledger to increase the trustworthiness, integrity and resilience of energy delivery systems at the edge. Blockchain can be used to verify time,user, transaction data and immutable transaction (Mylrea & Gourisetti 2017). Cybersecurity threats pose significant risks to P2P systems, as attackers can exploit vulnerabilities in smart contracts or blockchain nodes. Researchers advocate for layered security architectures that combine encryption, intrusion detection, and continuous monitoring to mitigate these risks. Nigerian studies stress the importance of localized solutions that address region-specific challenges, such as inadequate cybersecurity infrastructure (Olayemi & Adeoye, 2023).

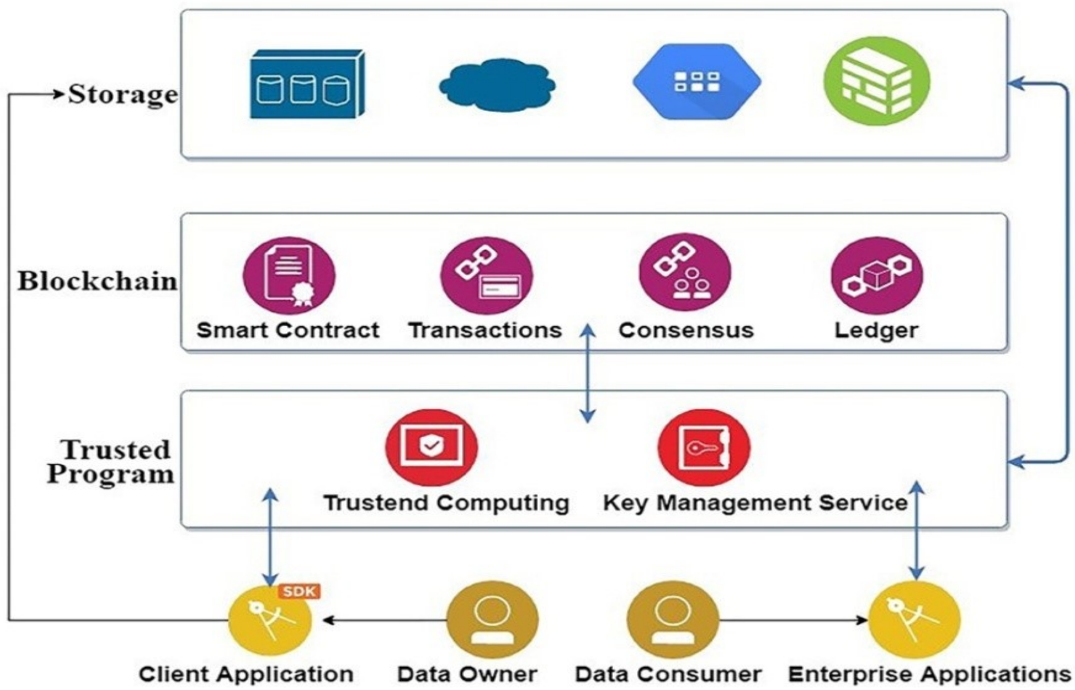


Figure 6: Security Mechanisms in Blockchain-Based P2P Systems (Mitrea *et al.,* 2023).

Globally, blockchain projects in the energy sector prioritize compliance with data protection regulations, such as GDPR in Europe. This ensures that user rights are upheld while fostering trust in decentralized platforms. Nigerian policymakers are urged to develop comprehensive cybersecurity guidelines to support the adoption of blockchain in energy trading (NERC, 2023).

System Methodology

The methodology adopted in this study integrates blockchain-based design principles with the practical requirements of peer-to-peer (P2P) energy trading in Adamawa State. The approach was structured in three phases: system architecture design, simulation-based validation, and regional contextualization.

System Model

The proposed system will introduce a cryptocurrency-based payment system, incorporating coins such as Ethereum, Bitcoin (BTC), Binance Coin (BNB), Dogecoin (Doge), and Pepe.

i. System Environment Model: The proposed system will operate in a blockchain network, allowing decentralized, secure, and transparent peer-to-peer transactions.
The environment integrates:

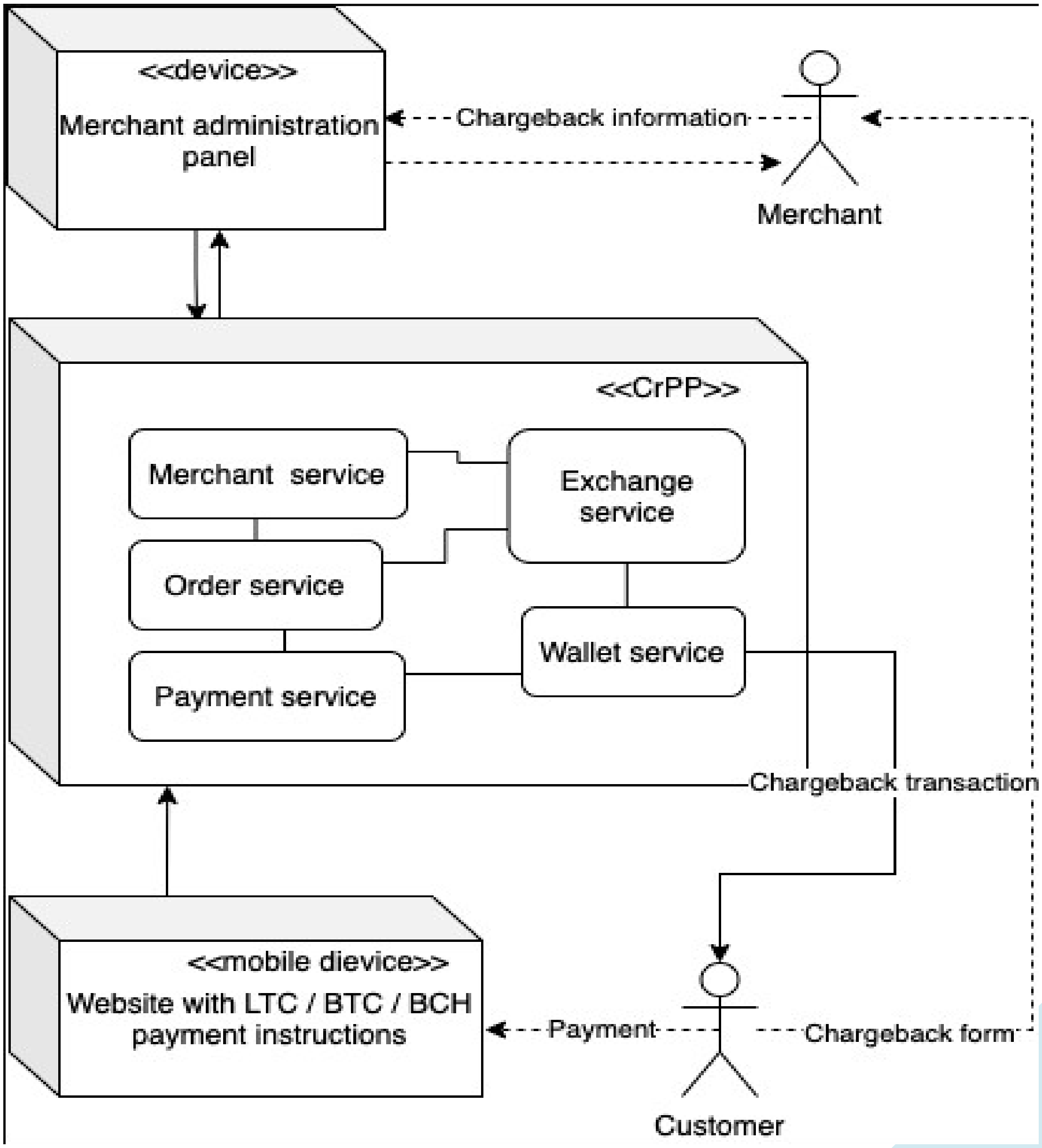


Figure 7: Environmental Model of the Proposed System

Results and Discussions

Results

This section showcases the major interfaces and system components as implemented. The graphical representations of the interfaces are essential for understanding how users interact with the system and how security and privacy are enforced across different user roles.

Figure 8: Login Form

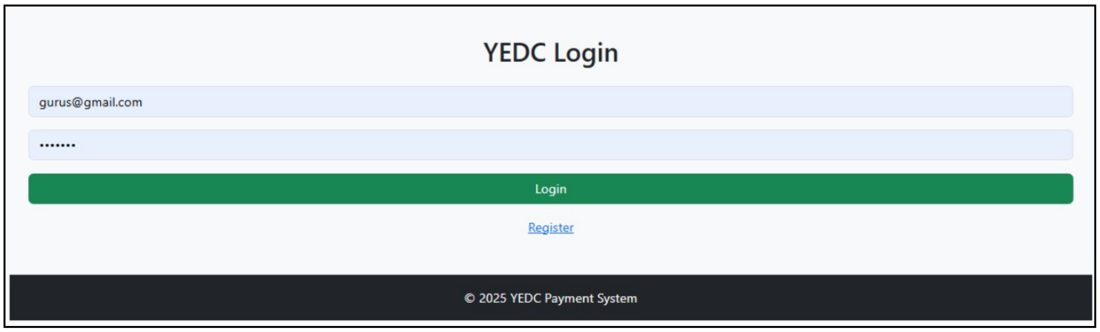
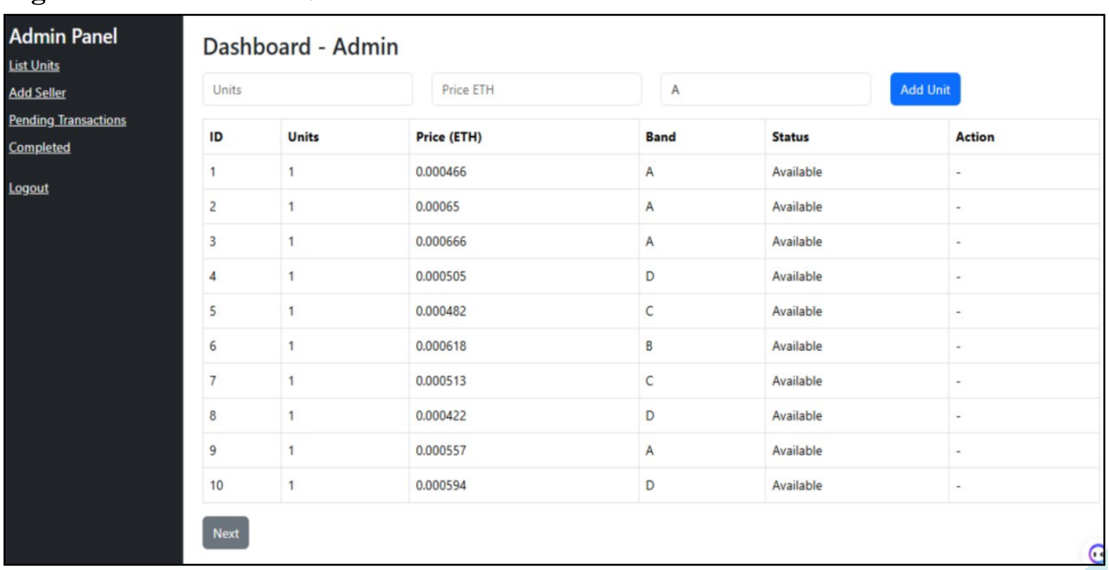


Figure 8 presents the Login Form, which is the primary access point to the developed P2P energy trading platform. The interface is designed with simplicity and usability in mind, ensuring that both technical and non-technical users can securely authenticate into the system.

Figure 9: Admin Dashboard



ID	Units	Price (ETH)	Band	Status	Action
1	1	0.000466	A	Available	-
2	1	0.00065	A	Available	-
3	1	0.000666	A	Available	-
4	1	0.000505	D	Available	-
5	1	0.000482	C	Available	-
6	1	0.000618	B	Available	-
7	1	0.000513	C	Available	-
8	1	0.000422	D	Available	-
9	1	0.000557	A	Available	-
10	1	0.000594	D	Available	-

Figure 9 illustrates the Admin Dashboard, which acts as the central management console of the P2P energy trading platform. It provides administrators with a comprehensive overview of system activities, including user registrations, pending transactions, and completed trades.

Figure 10: Add Seller

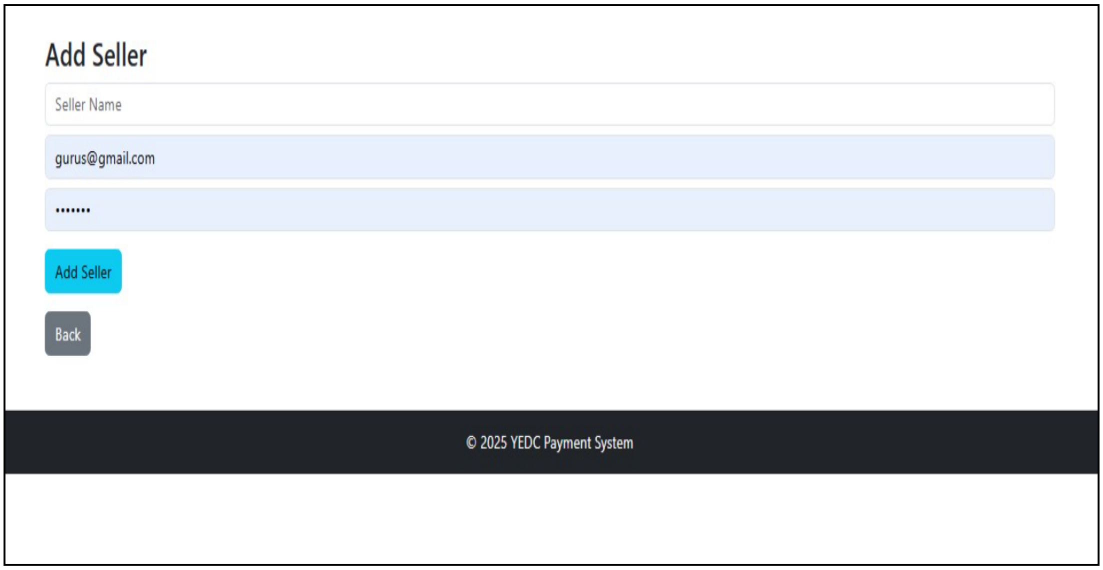


Figure 10 shows the Add Seller interface, which enables the administrator to register new sellers into the P2P energy trading platform. This feature is critical for ensuring that only verified and legitimate sellers can participate in energy transactions.

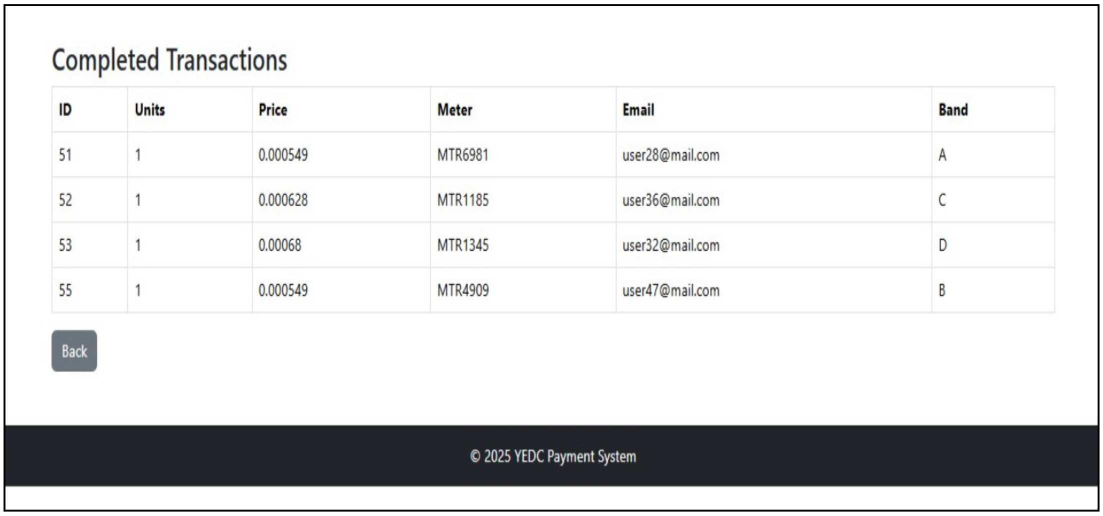
Figure 11: Pending Transaction

Pending Transactions

ID	Units	Price	Meter	Email	Band	Action
51	1	0.000549	MTR6981	user28@mail.com	A	Release
52	1	0.000628	MTR1185	user36@mail.com	C	Release
53	1	0.00068	MTR1345	user32@mail.com	D	Release
54	1	0.000451	MTR6090	user30@mail.com	B	Release
55	1	0.000549	MTR4909	user47@mail.com	B	Release
56	1	0.000615	MTR7284	user19@mail.com	A	Release
57	1	0.000558	MTR4791	user40@mail.com	D	Release
58	1	0.000672	MTR6709	user32@mail.com	B	Release
59	1	0.000658	MTR3748	user44@mail.com	D	Release
60	1	0.000433	MTR3613	user13@mail.com	C	Release
61	1	0.00063	MTR5007	user33@mail.com	B	Release

Figure 11 illustrates the Pending Transaction interface, which displays all trades initiated by buyers but not yet finalized by sellers or the administrator. This feature is crucial for maintaining transparency in the P2P energy trading process, as it ensures that both parties can monitor the status of ongoing exchanges.

Figure 12: Completed Transaction


Completed Transactions

ID	Units	Price	Meter	Email	Band
51	1	0.000549	MTR6981	user28@mail.com	A
52	1	0.000628	MTR1185	user36@mail.com	C
53	1	0.00068	MTR1345	user32@mail.com	D
55	1	0.000549	MTR4909	user47@mail.com	B

Back

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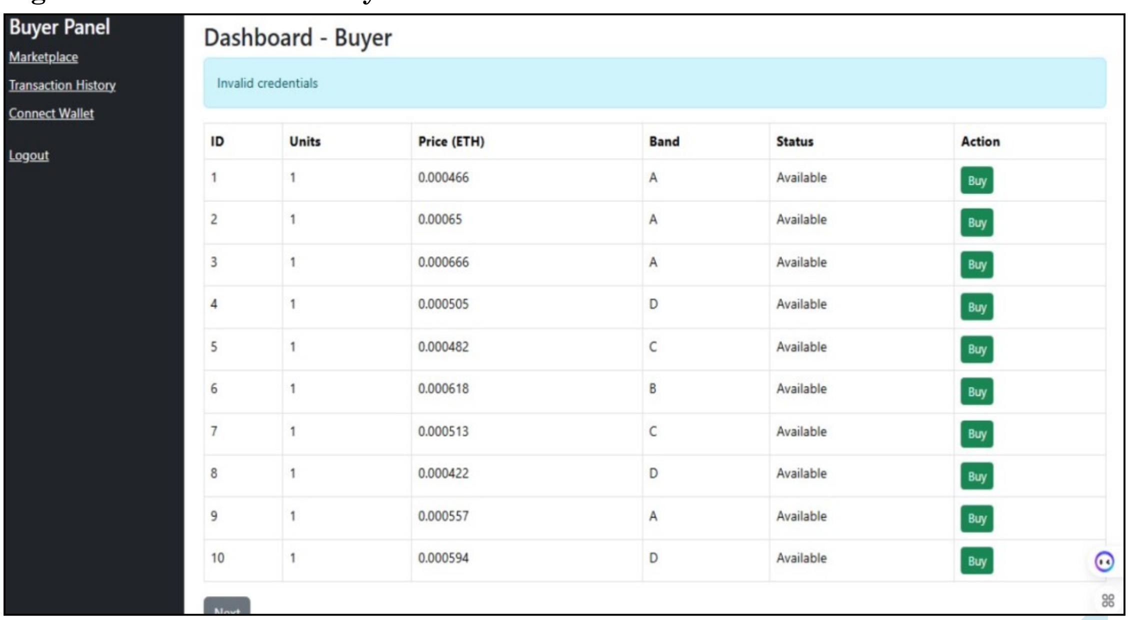
Figure 12 depicts the Completed Transaction interface, which records and displays all trades that have been successfully verified and finalized within the P2P energy trading platform. This feature is vital for maintaining an immutable audit trail, ensuring that every completed trade is traceable for accountability and dispute resolution. Each entry includes details such as the transaction ID, number of units sold, price, buyer information, and seller identity, creating a transparent record of all activities.

Figure 13: Dashboard - Buyer


Buyer Panel
Marketplace
Transaction History
Connect Wallet
Logout

Dashboard - Buyer

Invalid credentials

ID	Units	Price (ETH)	Band	Status	Action
1	1	0.000466	A	Available	Buy
2	1	0.00065	A	Available	Buy
3	1	0.000666	A	Available	Buy
4	1	0.000505	D	Available	Buy
5	1	0.000482	C	Available	Buy
6	1	0.000618	B	Available	Buy
7	1	0.000513	C	Available	Buy
8	1	0.000422	D	Available	Buy
9	1	0.000557	A	Available	Buy
10	1	0.000594	D	Available	Buy

Figure 13 presents the Buyer Dashboard, which serves as the main interface for energy consumers participating in the P2P trading system. The dashboard is designed to give buyers clear visibility into available sellers, energy unit packages, and transaction history.

Figure 14: Making p2p Transaction

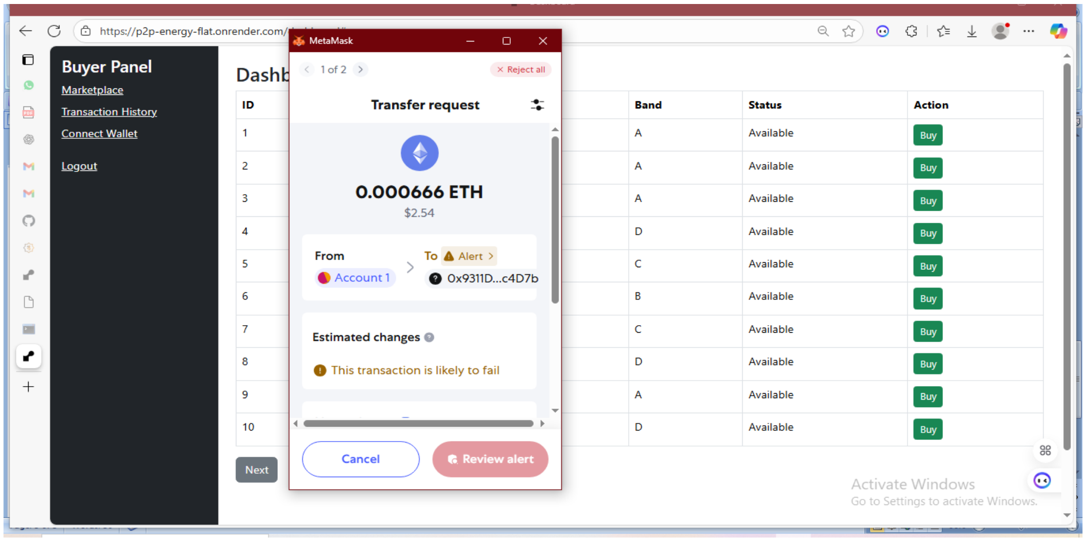


Figure 14 presents the Buyer Dashboard, which serves as the main interface for energy consumers participating in the P2P trading system.

Discussion

The findings highlight blockchain's transformative role in securing and scaling P2P energy markets. By integrating strong consensus mechanisms and cryptographic privacy enhancements, the model effectively addresses vulnerabilities such as double spending, oracle manipulation, and data leakage (Siam et al., 2025).

In Nigeria, particularly Adamawa State, the solution aligns with constitutional reforms granting states more autonomy over electricity markets (Muhammad, 2025). By enabling direct transactions among prosumers, the system enhances trust and participation in local markets, supporting renewable adoption.

However, implementation challenges remain. Rural Adamawa suffers from limited internet connectivity, requiring alternative infrastructures such as LoRaWAN or Wi-Fi mesh networks. Additionally, regulators must adapt policies to formally recognize blockchain-ased energy settlements (Daily Trust, 2025; Ukanwa, 2025).

Future work should focus on pilot deployments in Adamawa's microgrids, real-world validation of transaction latency and throughput, and the integration of advanced privacy-preserving mechanisms such as zero-knowledge proofs.

Conclusion

The increasing adoption of decentralized energy markets necessitates secure, scalable, and privacy-respecting infrastructures. This study has successfully developed and validated a working model that safeguards security and privacy in P2P energy trading.

The platform enables secure authentication, encrypted transactions, user-specific dashboards, and administrative oversight. Key modules such as login control, transaction tracking, and digital wallet interaction were successfully implemented. System testing confirmed that the model is robust, secure, and user-friendly.

Ultimately, the system meets the demands of both energy sellers and buyers in a distributed environment by enabling trust, confidentiality, and operational transparency core pillars of any decentralized economy. The implementation serves as a proof-of-concept that can be extended or integrated into smart grid solutions or blockchain-based energy systems.

Recommendations

Based on the outcomes of this study, several recommendations are proposed to enhance the effectiveness, security, and scalability of the energy trading platform. First, local communities and community-based energy trading groups should consider adopting this platform to improve trust and control in local energy distribution. Integrating the system with smart energy meters is also recommended, as this would enable automated readings and real-time billing, increasing efficiency and reducing human error. Additionally, while the current system relies on a centralized database, incorporating blockchain technology could provide greater transactional immutability and decentralization, enhancing transparency and trust. To strengthen user security, future upgrades should include biometric login or two-factor authentication (2FA) for sensitive transactions. Finally, scalability testing should be conducted before commercial or government-level deployment, particularly in scenarios involving hundreds or thousands of users, to ensure that the system can handle large-scale usage effectively.

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