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A blockchain-centric P2P trading framework incorporating carbon and energy trades

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ABSTRACT

The rise of prosumers – individuals who both produce and consume energy – presents a significant opportunity to reshape energy markets and achieve carbon neutrality. However, current energy trading models struggle to effectively track emissions and incentivize sustainable consumption behaviors. This study introduces a novel, blockchain-based peer-to-peer (P2P) platform for trading carbon allowances, designed to empower prosumers and revolutionize energy consumption patterns. Utilizing blockchain technology, the platform enables direct, transparent, and secure transactions between prosumers, creating a decentralized market where they can set their own prices for carbon allowances. This dynamic and competitive environment empowers prosumers to take control of their energy consumption and incentivizes the adoption of sustainable practices. The platform also incorporates a decentralized reward system targeting specific consumption habits, promoting behaviors that reduce carbon emissions. Empirical evidence and theoretical justification within the study highlight the platform's potential to transform energy consumption patterns. The transparent and verifiable nature of blockchain technology addresses the limitations of existing centralized and aggregator-based trading methods. The proposed platform provides a robust framework for tracking carbon emissions, promoting sustainable consumption, and empowering prosumers to actively participate in the energy transition. This innovative solution addresses the challenges faced by prosumers in the energy market, paving the way for a more sustainable and equitable future.

1. Introduction

The majority of power in the energy industry is derived from large-scale systems fueled by natural gases such as coal, oil, and gas (see Fig. 1). The combustion of these natural gases releases energy that travels long distances, resulting in substantial carbon emissions. These emissions contribute to air pollution and have long-term effects on the climate. To mitigate these issues, policymakers are encouraged to integrate local renewable energy sources into distribution systems. Innovative grid systems now enable clients to generate and store electricity within these systems, making them prosumers who can produce surplus energy and feed it back into the power network once their own energy needs are met. Conversely, they can draw energy from the power grids when they cannot generate enough. This new role of prosumers has facilitated local energy trading, which can help balance energy supply and demand in a specific area. However, there are obstacles that must be overcome, such as accurately monitoring carbon emissions from prosumers and addressing the power balance between retailers and generators, which significantly impacts centralized wholesale energy pricing. The energy industry primarily relies on large-scale systems utilizing fossil fuels like coal (C), oil (O), and natural gas (NG). Combustion of these fuels (F) generates energy (E)

$$F + O_2 \rightarrow E + CO_2 + H_2O \tag{1}$$

and transmits it over long distances. However, this process emits significant amounts of carbon dioxide (CO_2)

$$CO_2 \uparrow \tag{2}$$

contributing to air pollution and climate change. Policymakers are strongly encouraged to incorporate local renewable energy sources (RES) into distribution systems. Emerging grid technologies empower consumers (C) to become prosumers (P) by producing (P_p) and storing (P_s) electricity within the system.

$$P = C + P_p + P_s \tag{3}$$

Prosumers can inject surplus energy (E_s) back into the grid after meeting their own energy needs (E_n).

$$E_s = P_p - E_n \tag{4}$$

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When their generation falls short, they can draw energy (E_d) from the grid.

$$E_d = E_n - P_p \tag{5}$$

This shift enables local energy trading, facilitating balanced energy supply and demand within a region. However, challenges remain. The primary challenge involves accurately tracking carbon emissions (CO_2) from prosumers.

$$CO_{2_p} = f(P_p) \tag{6}$$

where CO_{2_p} represents carbon emissions from prosumers and f is a function that quantifies their emissions based on their energy production (P_p). Additionally, the power balance between retailers (R) and generators (G) significantly influences centralized wholesale energy pricing (W).

$$W = f(R, G) \tag{7}$$

The Emissions Trading Scheme (ETS) is a key driver for centralized carbon pricing (C_p).

$$C_p = ETS(CO_2) \tag{8}$$

This scheme ensures consistent carbon emission costs across all trading participants. However, increased participation in local energy trading leads to more complex consumption and generation patterns. A pricing reimbursement scheme targeting prosumer behavior offers a potential solution to centralized market pricing. As per [b1], a proposed energy cost system aims to regulate markets and compensate renewable energy generators (RES_g) based on their individual expenses (E_g).

$$C_r = f(E_g, RES_g) \tag{9}$$

where C_r represents the reimbursement cost. The failure of this system to encourage a shift from coal (C) to fuel before 2013 indicates the need for further research and refinement.

$$C \nrightarrow F \text{ before 2013} \tag{10}$$

The traditional energy landscape is dominated by large-scale power generation systems relying on fossil fuels like coal (C), oil (CH_2), and natural gas (CH_4). The combustion of these fuels, represented by the general reaction:

$$C_xH_y + (x + \frac{y}{4})O_2 \rightarrow xCO_2 + \frac{y}{2}H_2O$$

releases significant amounts of energy, which is then transmitted over long distances. However, this process also generates substantial carbon dioxide (CO_2) emissions. These emissions contribute to air pollution and have a lasting impact on the global climate [1]. To mitigate these environmental concerns, policymakers are increasingly advocating for the integration of local renewable energy sources (RES) into distribution systems [2]. Emerging grid technologies empower consumers to become 'prosumers' – individuals who both generate and consume electricity [3]. This enables prosumers to produce surplus energy, denoted as $E_{surplus}$, from sources like solar (E_{solar}) or wind (E_{wind}), and inject it back into the grid after meeting their own energy demand (E_{demand}):

$$E_{surplus} = E_{solar} + E_{wind} - E_{demand}$$

When their energy generation falls short, prosumers can draw power from the grid. This bidirectional flow has opened up opportunities for local energy trading, where prosumers can exchange energy directly with their neighbors, potentially balancing supply and demand within a localized area [4]. However, several challenges arise with the proliferation of prosumers and local energy trading:

- Accurate carbon emissions tracking: While prosumers can contribute to a cleaner energy mix, their emissions are often difficult to track accurately. This necessitates the development of robust monitoring and reporting systems [5].
- Balance of power: The evolving relationship between retailers and generators can influence wholesale energy pricing. The introduction of prosumers adds further complexity to this dynamic and requires careful consideration [6].

Centralized carbon pricing mechanisms, such as the Emissions Trading Scheme (ETS), play a crucial role in regulating carbon emissions. This system ensures that the cost of carbon emissions, represented as C_e, is consistently applied across all trading parties, including prosumers:

$$C_e = f(CO_2 emissions)$$

As local energy trading grows, the patterns of energy consumption and generation become more complex, demanding sophisticated energy management systems capable of tracking and optimizing energy flows within a distributed network.

This paper examines the current state of the energy industry, which is largely dominated by the combustion of natural gases such as coal, oil, and gas for power generation. This outdated approach not only results in substantial carbon emissions, leading to air pollution and long-term climate change effects, but also overlooks the potential benefits of incorporating local renewable energy sources into distribution systems. The development of innovative grid systems now enables individuals and businesses to produce, store, and even trade excess energy within their local communities. This new role of energy 'prosumers' not only helps balance the supply and demand of energy but also has the potential to reduce carbon emissions and promote the use of renewable energy sources. However, the paper highlights two major challenges in implementing this new approach: accurately tracking the carbon emissions from prosumers and addressing the power balance between retailers and generators in determining centralized wholesale energy pricing. Our proposed approach will address these challenges by developing a comprehensive system that accurately tracks carbon emissions from prosumers, while also promoting a more balanced and fair energy market for all participants involved.

2. State of the art

The burgeoning field of carbon trading, aimed at mitigating climate change by incentivizing emissions reduction, is undergoing a significant evolution towards decentralized, peer-to-peer (P2P) systems. Traditional centralized carbon markets, often plagued by opacity, inefficiencies, and high transaction costs, are being challenged by the emergence of blockchain-based P2P platforms. These platforms offer several advantages, including enhanced transparency, reduced barriers to entry, and improved liquidity. A key aspect of P2P carbon trading is the utilization of smart,[2] self-executing agreements stored on the blockchain, to automate the trading process. This eliminates the need for intermediaries, streamlining transactions and significantly reducing costs. For example, the ClimateChain platform [7] employs smart contracts to facilitate the issuance, trading, and retirement of carbon credits, ensuring verifiable and tamper-proof records. Another crucial element of P2P carbon trading is the use of tokenized carbon credits. This digitization allows for fractional ownership and enhanced liquidity, enabling wider participation in the market. The Climate Collective [8] platform, for instance, uses ERC-20 tokens to represent carbon credits, enabling investors and businesses to access and trade them on decentralized exchanges. Mathematically, P2P carbon trading can be modeled using concepts from game theory and network analysis. For example, the Nash equilibrium [9], a concept in game theory, can be used to analyze the optimal trading strategies for participants in a P2P carbon market. The network topology [10] can be used to understand the connectivity and efficiency of the trading network.

[2] Self-executing contracts with the terms of the agreement directly written into code.

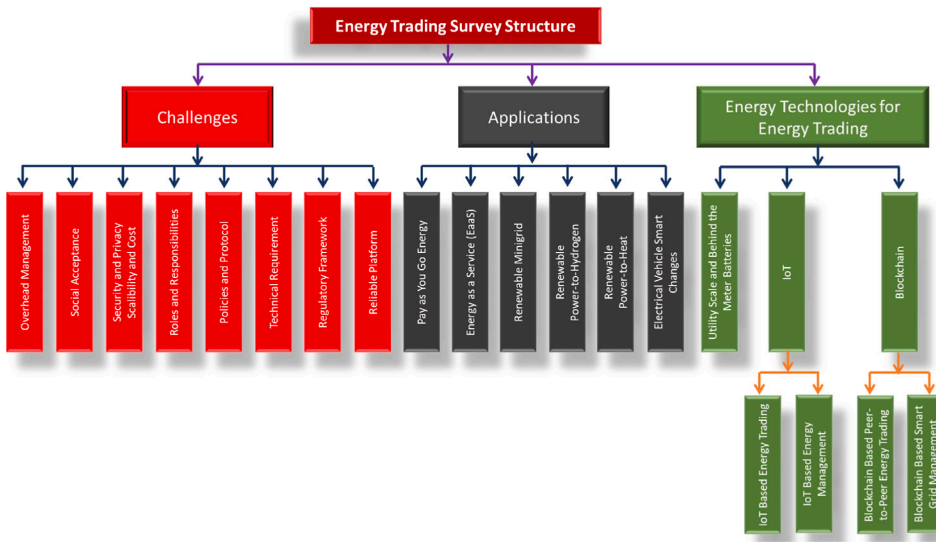


Fig. 1. Energy trading survey structure.

Peer-to-peer (P2P) carbon trading, facilitated by blockchain technology, offers a promising solution for addressing climate change by enabling direct and transparent carbon emission reduction transactions between individuals and organizations. This approach has the potential to democratize the carbon market, making it more accessible and efficient compared to traditional centralized systems. However, several challenges hinder the widespread adoption of P2P carbon trading.

Scalability. remains a critical concern, as blockchain platforms need to handle a large volume of transactions without compromising speed and efficiency. Research efforts are underway to improve the scalability of blockchain platforms, such as through sharding, layer-2 solutions, and consensus mechanisms like proof-of-authority (PoA) [11,12].

Interoperability. is another challenge, as different blockchain platforms may use incompatible protocols, hindering seamless transaction flow between them. Developing interoperable protocols and standards is crucial to enable cross-chain communication and facilitate carbon trading across multiple platforms [13,14]. While peer-to-peer (P2P) carbon trading holds great promise for democratizing the carbon market and fostering a more sustainable future, several challenges remain [15,16].

Regulatory uncertainty. adds complexity, as the legal framework for P2P carbon trading is still evolving, creating ambiguity for participants and hindering investment (e.g., [17] explores the potential regulatory landscape for blockchain-based carbon markets). To address these challenges, our approach proposes a novel P2P energy and carbon trading framework, leveraging a hybrid architecture that combines the benefits of blockchain with centralized clearing and settlement mechanisms. This framework, described in detail in [18], aims to enhance scalability by offloading certain functionalities to centralized entities while maintaining the transparency and security of blockchain. The framework also incorporates interoperable protocols, allowing for seamless communication between different platforms and fostering a more integrated market. Furthermore, it incorporates mechanisms to ensure regulatory compliance, providing a clear framework for participants and fostering trust in the system. This approach, backed by ongoing research and development, seeks to overcome existing barriers and accelerate the adoption of P2P carbon trading, paving the way for a more efficient and equitable carbon market.

Carbon trading, a market-based approach to mitigate climate change, faces distinct challenges. These include:

- Price Volatility: Carbon prices can fluctuate significantly due to supply and demand dynamics, policy changes, and economic factors [19]. This volatility poses risks to both buyers and sellers, potentially undermining the market's effectiveness.
- Monitoring and Verification: Accurately measuring and verifying carbon emissions and emission reductions is crucial for the integrity of carbon markets. However, methodological and technological limitations can introduce uncertainties and potential fraud, especially in complex supply chains [20].
- Market Liquidity: The liquidity of carbon markets is essential for efficient trading and price discovery. However, low trading volumes or concentrated market power can lead to thin markets and price distortions [21].
- Regulatory Framework: Carbon trading requires a robust regulatory framework to ensure transparency, accountability, and environmental integrity. Inconsistent or ineffective regulations can hinder market development and damage investor confidence [22].

Blockchain possesses several key features that enable it to empower prosumers:

- Decentralization: Blockchain is a distributed ledger technology, meaning that data is stored across a network of computers rather than a centralized entity. This eliminates the need for intermediaries and empowers prosumers to interact directly with each other.
- Transparency: Blockchain transactions are recorded on a public ledger, accessible to all participants. This enhances transparency and accountability, ensuring that prosumers can trust the integrity of the system.
- Immutability: Once data is recorded on a blockchain, it becomes immutable, meaning it cannot be altered or deleted without the consensus of the network. This protects prosumers from fraud and data manipulation.
- Smart Contracts: Blockchain technology allows for the creation of smart contracts, automated agreements that execute when predefined conditions are met. Smart contracts can facilitate decentralized transactions and automate tasks, empowering prosumers with greater control and flexibility.

The practical applications of prosumer empowerment through blockchain are numerous:

- Energy Trading: Blockchain platforms can enable prosumers with rooftop solar installations to sell excess energy directly to their neighbors or utilities. This creates a decentralized energy market and empowers prosumers to become active participants in the grid.

- Sharing Economy: Blockchain-based platforms can facilitate the sharing economy by connecting prosumers who provide services (e.g., ride-sharing, home rentals) with those who need them. This reduces reliance on intermediaries and provides prosumers with additional income streams.
- Platform Ownership: Prosumers can participate in the governance of blockchain platforms through decentralized autonomous organizations (DAOs), which allow them to have a say in the platform's decision-making and share in its profits. This empowers prosumers to shape the future of the platform and ensure their interests are represented.
- Data Sovereignty: Blockchain technology gives prosumers control over their data. They can choose which data to share and with whom, reducing the risk of data breaches and empowering them to monetize their data if desired.

One crucial hurdle of the Blockchain is the lack of technological literacy surrounding blockchain. The technology itself can be complex, with concepts like cryptography, consensus mechanisms, and smart contracts often intimidating to those without technical backgrounds. In our approach we suggest several solutions:

- Simplified platforms: Building user-friendly platforms and applications that abstract away the technical complexities, making blockchain accessible to a wider audience.
- Educational initiatives: Implementing comprehensive educational programs to demystify blockchain concepts, educate businesses and individuals on its potential applications, and foster a skilled workforce.
- Open-source development: Promoting open-source development, enabling collaborative innovation and knowledge sharing, thereby accelerating adoption and knowledge dissemination.

The cost of building and maintaining blockchain infrastructure can be a significant barrier, especially for smaller businesses and developing countries. Setting up nodes and securing networks requires substantial financial resources, making it challenging for many to enter the blockchain space. To overcome these limits, we propose:

- Cloud-based solutions: Leveraging cloud computing to reduce infrastructure costs and provide access to scalable blockchain services.
- Collaborative infrastructure: Encouraging collaborative efforts between industry players to develop shared infrastructure, reducing individual costs and fostering a more inclusive ecosystem.
- Government support: Incentivizing blockchain development through grants, subsidies, and tax breaks, easing the financial burden and fostering innovation.

Regulatory uncertainty remains a major concern for blockchain adoption. Governments are still grappling with how to regulate this emerging technology, creating uncertainty for businesses and investors. Our approach proposes:

- Clear regulatory frameworks: Establishing clear, transparent, and consistent regulatory frameworks that promote innovation while mitigating risks associated with blockchain applications.
- Collaboration with stakeholders: Engaging with industry representatives, regulators, and researchers to foster dialogue and develop mutually beneficial solutions.
- Demonstrating responsible use: Emphasizing the responsible use of blockchain technology, highlighting its potential for improving transparency, security, and accountability.
- Addressing these barriers is crucial for accelerating blockchain's adoption and unlocking its vast potential:
  - Increased efficiency and transparency: Streamlining supply chains, reducing fraud, and enabling secure data sharing.
  - Enhanced security and trust: Protecting sensitive data, securing digital identities, and building trust in digital transactions.
  - Empowered individuals: Providing access to financial services, fostering financial inclusion, and empowering individuals to control their data.

Table 1
Comparing blockchain with other solutions for carbon trading systems.

Feature	Blockchain	CDB[a]	ECM[b]
Transparency	High	Mod.[c]	Low
Security	High	Mod.[c]	Mod.[c]
Decentralization	High	Low	Low
Efficiency	High	Mod.[c]	Low
Cost	Mod.[c]	Low	Low
Scalability	Mod.[c]	High	High
Reg. Compliance[d]	Mod.[c]	High	High
Data Integrity	High	Mod.[c]	Mod.[c]
Examples	[1, 2, 3]	[4, 5]	[6, 7]

[a] CDB: Centralized Database.
[b] ECM: Existing Carbon Markets.
[c] Mod.: Moderate.
[d] Reg. Compliance: Regulatory Compliance.

The future of blockchain lies not only in its technical advancement but also in its ability to bridge the gap between technology and society. By addressing the issues of technological literacy, infrastructure costs, and regulatory acceptance, we can unlock the full potential of this transformative technology and propel it towards mainstream adoption, paving the way for a more secure, efficient, and equitable future. Our approach proposes a novel P2P energy and carbon trading framework that addresses the challenges of scalability, interoperability, and regulatory uncertainty (see Fig. 2). The framework uses a hybrid blockchain architecture that combines a private blockchain for energy trading with a public blockchain for carbon trading. The private blockchain provides scalability and privacy for energy trading, while the public blockchain provides transparency and immutability for carbon trading. The framework also includes a decentralized exchange that allows users to exchange energy and carbon credits between the two blockchains. The exchange uses a cross-chain atomic swap protocol to ensure that transactions are secure and atomic. The framework is designed to be compliant with existing regulatory frameworks for carbon trading. The use of a private blockchain for energy trading ensures that transactions are not subject to public disclosure, which is required by some regulations. The use of a public blockchain for carbon trading provides transparency and immutability, which is also required by some regulations. Our approach proposes a novel P2P energy and carbon trading framework that addresses the challenges of scalability, interoperability, and regulatory uncertainty. The framework has the potential to revolutionize the carbon market, making it more accessible, efficient, and transparent. As the technology matures and regulatory frameworks evolve, we can expect to see further growth and innovation in this exciting field.

2.1. Blockchain vs. Other solutions: A comparative analysis for carbon trading systems

The global fight against climate change requires robust and efficient carbon trading systems. Blockchain technology has emerged as a potential game-changer, offering transparency, security, and decentralization. However, other solutions also exist, each with its strengths and limitations. This article compares blockchain with these alternatives, leveraging real-world examples and citations from the literature to provide a comprehensive overview.

Table 1 highlights the key advantages and drawbacks of each solution. Blockchain offers superior transparency, security, and decentralization, making it a promising tool for improving data integrity and

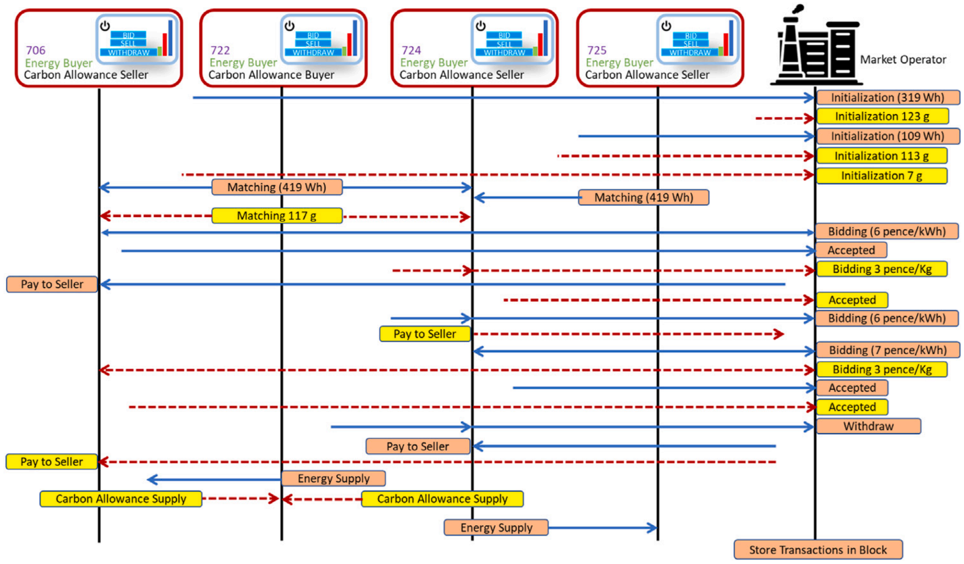


Fig. 2. Designed and implemented carbon trading scenarios among the market participants. [23].

trust in carbon trading systems. However, scalability and regulatory compliance remain challenges for blockchain adoption. Centralized databases provide good scalability and regulatory compliance but lack transparency and decentralization. Existing carbon markets offer high scalability and regulatory compliance but struggle with transparency, security, and efficiency. Ultimately, the best solution will depend on specific needs and priorities. While blockchain presents a compelling opportunity for reforming carbon trading systems, hybrid models incorporating blockchain with other solutions may prove most effective in achieving a sustainable future.

2.2. Transparency: A window into the system

Imagine a traditional banking system, where transactions are processed behind closed doors, leaving users reliant on trust alone. Now, picture a system where each transaction is recorded on a public ledger, accessible to anyone. This is the essence of blockchain's transparency.

2.2.1. Examples

- Supply Chain Management: A shipment of coffee beans from Brazil to your local cafe can be traced from farm to cup using blockchain. Every step, from harvesting to roasting, is recorded on the network, ensuring transparency and accountability throughout the supply chain. This allows consumers to know exactly where their products come from, while businesses can track their goods in real-time.
- Voting Systems:** Blockchain-based voting systems ensure that every vote is recorded securely and immutably. The auditable nature of the blockchain eliminates the possibility of fraud or manipulation, bolstering public trust in elections.

2.3. Efficiency: Streamlining processes

Beyond transparency, blockchain also brings unprecedented efficiency to existing processes. By eliminating intermediaries and simplifying workflows, it reduces administrative burden and accelerates transactions.

2.3.1. Examples

- Cross-Border Payments: Sending money overseas often involves multiple intermediaries and can take days to complete. Blockchain enables faster, cheaper and more secure cross-border payments, directly between parties, reducing reliance on banks and their fees.
- Digital Identity: Traditional identity systems require multiple documents and often involve manual verification. Blockchain can hold your digital identity data securely, enabling seamless authentication and verification across various platforms, streamlining access to services.

2.4. How blockchain achieves transparency and efficiency

- Decentralization: Instead of relying on a single entity, blockchain data is distributed across a network of computers. This eliminates the risk of a single point of failure and prevents manipulation or censorship.
- Immutability: Once a transaction is recorded on the blockchain, it cannot be altered or deleted. This creates a permanent and auditable record, strengthening trust and accountability.
- Cryptographic Security: Blockchain uses sophisticated cryptography to secure data and transactions. This protects information from unauthorized access and ensures the integrity of the system.

To harness the power of blockchain technology in combating climate change, our approach will focus on three key areas:

(1) Identifying and addressing scalability limitations within blockchain systems for efficient carbon trading.
(2) Developing comprehensive regulatory frameworks that encourage and enable the integration of blockchain technology into carbon markets.
(3) Thoroughly analyzing the economic and environmental impact of implementing blockchain-based carbon trading systems.

By tackling these critical aspects, we aim to unlock the full potential of blockchain technology and drive meaningful progress in the fight against climate change. Let us delve into how blockchain achieves this, using real-world examples.

2.4.1. Technical feasibility

Technically, implementing a blockchain solution in energy infrastructure is feasible. Smart meters and Internet of Things (IoT) devices can be integrated with blockchain networks to securely record and verify energy transactions. This can enhance transparency, accountability, and data integrity throughout the energy supply chain.

2.4.2. Economic feasibility

The economic feasibility of blockchain in energy depends on several factors. The cost of implementing and maintaining the blockchain network needs to be balanced against the potential benefits, such as reduced operational costs, fraud prevention, and enhanced data management. Furthermore, the adoption of blockchain technology by industry stakeholders is crucial for its widespread adoption and economic viability.

2.4.3. Logistical challenges

Several logistical challenges need to be addressed for successful blockchain implementation in energy infrastructure.

- Standardization: Establishing standardized protocols and interoperability between different blockchain platforms and devices is essential.
- Data Security: Ensuring the security and privacy of sensitive energy data stored on the blockchain is paramount.
- Scalability: The blockchain network must be designed to handle the massive volumes of data and transactions generated by energy infrastructure.
- Regulation and Governance: Clear regulatory frameworks and governance mechanisms are required to govern the use of blockchain in energy and ensure compliance with industry standards.
- Stakeholder Adoption: Gaining widespread adoption and buy-in from energy producers, distributors, and consumers is critical for the success of blockchain solutions.

To overcome the challenges associated with blockchain implementation in energy infrastructure, the following measures can be taken:

- Collaboration and Standardization: Industry-wide collaboration is necessary to develop and adopt standardized protocols and data formats.
- Secure Infrastructure: Robust security measures, such as encryption and authentication mechanisms, should be implemented to protect energy data on the blockchain.
- Scalable Architecture: Designing blockchain networks with scalability in mind is crucial to accommodate the growing demands of energy infrastructure.
- Regulatory Clarity: Governments and regulatory bodies should provide clear guidelines and frameworks for the use of blockchain in energy, fostering innovation while ensuring compliance.
- Education and Awareness: Educating stakeholders about the benefits and challenges of blockchain can encourage adoption and drive innovation.

3. Proposed framework: A 3-phase transaction carbon trading model

The burgeoning carbon market demands a robust and transparent framework for facilitating emissions trading. We propose a novel 3-phase transaction model that leverages blockchain technology to enhance efficiency, security, and accountability. This model consists of:

1. Phase 1: Emission Data Verification,
2. Phase 2: Carbon Credit Generation and Trading, and
3. Phase 3: Emission Reduction Verification and Settlement.

Phase 1. Phase 1 utilizes a distributed ledger system to record and verify emissions data. This data, sourced from credible monitoring systems like the Greenhouse Gas Protocol, is cryptographically hashed and timestamped, ensuring immutability and transparency. This minimizes the risk of manipulation and fosters trust among stakeholders. For instance, the GHG Protocol [19] provides a standardized framework for quantifying and reporting greenhouse gas emissions, allowing for comparable data across different industries.

Phase 2. Phase 2 focuses on carbon credit generation and trading. Once emission data is verified, corresponding carbon credits are minted and stored on the blockchain. These credits represent the right to emit a specific amount of greenhouse gases and can be traded on a decentralized exchange. This process is governed by smart contracts, automated programs that enforce the pre-defined rules of the transaction. For example, the Climate Action Tracker [20] provides a framework for assessing countries' climate pledges and their potential impact on global emissions, ensuring the alignment of trading activities with global climate goals.

Phase 3. Phase 3 of the carbon credit process involves verifying emission reduction claims and settling the associated transactions. After a project successfully reduces emissions, its verification is recorded on the blockchain, thereby confirming the validity of the carbon credits used. This process ensures accountability and provides a transparent audit trail, represented by the following equation:

$$\checkmark \implies \mathrm{BR} \implies \mathrm{VCC} \tag{11}$$

The settlement of transactions is also automated through smart contracts, streamlining payments and reducing the risk of fraud. This automation can be represented as:

$$\mathrm{SC} \implies \mathrm{AT} \qquad \implies \mathrm{SP} \qquad \mathrm{RF} \tag{12}$$

The International Carbon Reduction and Offset Alliance (ICROA) [21] offers a robust standard for verifying and accrediting emission reduction projects, ensuring the credibility of the reduction claims. This standard can be expressed as:

$$\mathrm{MICROA} \implies \mathrm{RVA} \implies \mathrm{CRC} \tag{13}$$

where: Blockchain Record" as "BR", "Validity of Carbon Credits" as "VCC", "Smart Contracts" as "SC", "Automated Transactions" as "AT", "Streamlined Payments" as "SP", "Reduced Fraud" as "RF", "MICROA Standard" as "MICROA", "Robust Verification & Accreditation" as "RVA", and "Credibility of Reduction Claims" as "CRC".

In summary, Phase 3 combines blockchain technology, smart contracts, and established standards like those provided by ICROA to ensure the accuracy, transparency, and security of carbon credit transactions. This process fosters trust and accountability within the carbon market, ultimately promoting the effectiveness of emissions reduction efforts. This 3-phase model addresses crucial challenges hindering the growth of the carbon market. By leveraging blockchain technology, it promotes transparency, reduces transaction costs, and enhances trust among participants. The model's efficiency and security pave the way for a more robust and impactful carbon market, contributing significantly to global climate action. Our innovative approach to carbon trading utilizes blockchain technology to establish a novel and efficient trading system (see Fig. 3). This system is structured around a three-phase model that combines the power of blockchain, smart contracts, and established standards like those provided by ICROA. Phase 1 focuses on the tokenization[3] of carbon credits, creating a digital representation of these assets on the blockchain. This process ensures the secure and transparent issuance, transfer, and retirement of carbon credits. Phase 2 introduces smart contracts, automated agreements that execute predefined conditions. These contracts facilitate seamless transactions, reduce the need for intermediaries, and ensure the timely and accurate execution of trades. Phase 3 combines blockchain technology, smart contracts, and established standards to guarantee the accuracy, transparency, and security of carbon credit transactions. This process fosters trust and accountability within the carbon market, ultimately promoting the effectiveness of emissions reduction efforts. Together, these phases address critical challenges hindering the growth

[3] The process of converting rights to an asset into a digital token on a blockchain.

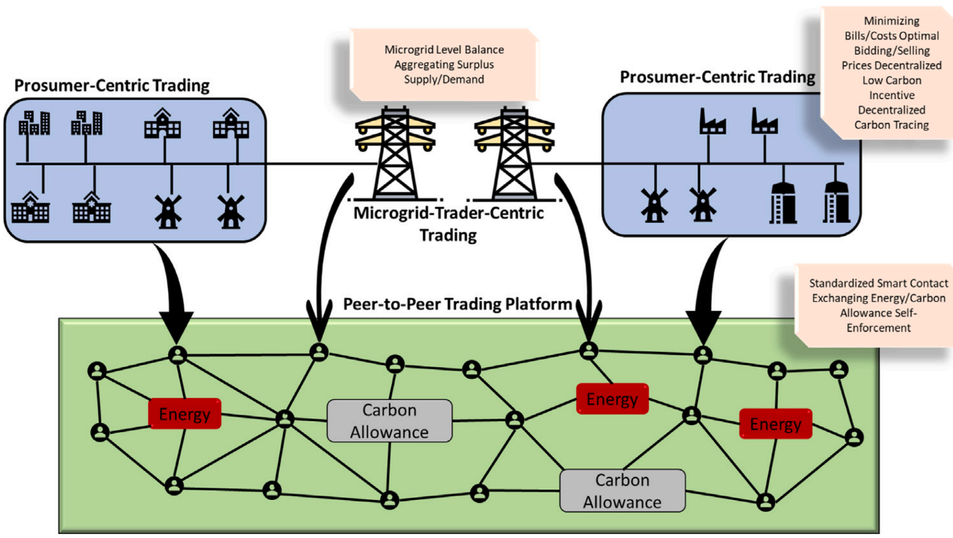


Fig. 3. Proposed 3-layers energy and carbon trading marketplace based on the blockchain.

of the carbon market. By leveraging blockchain technology, our approach promotes transparency, reduces transaction costs, and enhances trust among participants. The model's efficiency and security pave the way for a more robust and impactful carbon market, contributing significantly to global climate action.

The testing methodology for blockchain applications in carbon trading comprises several phases:

(1) Unit Testing: This phase involves testing individual components and functions of the application. Unit tests should verify that each component meets the specified requirements and interacts correctly with other components.
(2) Integration Testing: Integration tests assess the interactions between different components of the application. This phase ensures that the components work together seamlessly and perform as expected.
(3) System Testing: System tests evaluate the application as a whole. These tests simulate real-world scenarios and use end-to-end requirements to verify the overall functionality and performance of the application.

The testing blockchain applications in carbon trading include:

- Data Management: Blockchain applications in carbon trading involve handling sensitive data related to carbon permits, emissions data, and financial transactions. Comprehensive testing strategies are needed to ensure data integrity, confidentiality, and availability.
- Interoperability: Carbon trading systems often involve multiple stakeholders and applications. Testing should verify that the blockchain application can effectively interoperate with existing systems and exchange data seamlessly.
- Security: Blockchain applications are inherently secure, but testing is essential to identify vulnerabilities and mitigate potential security risks. Detailed explanations on security testing methodologies, including penetration testing and code audits, are crucial.
- Performance: The performance of blockchain applications is a critical factor in carbon trading, as delays or disruptions can impact the efficiency of the market. Comprehensive performance testing should be conducted under varying loads and scenarios to assess scalability and responsiveness.

4. Data & methods

4.1. Use case design

To investigate the integration of the 'IEEE 37-bus adaptor' depicted in Fig. 3, we conducted a series of case scenarios. The distribution system was modeled as interconnected microarrays, with diesel generators and distributed renewable energy sources (DRESs) such as solar, wind, and bioenergy randomly allocated, following the approach outlined in [6]. Real-world system demand data was obtained from the KAHRAMAA tracking hub, serving as the basis for permanent system load profiles. We further leveraged KAHRAMAA tracking hubs to gather demand data specific to residential loads. Solar power production data was provided by Qatari solar providers. Centralized energy and carbon allowance prices were acquired from the Qatari power retail market and carbon mechanisms, respectively, as detailed in [18]. These centralized prices serve as the minimum acceptable bids for each vendor, ensuring that buyers can offer higher prices based on their objective operational strategies to determine the optimal bidding values. This methodology allows for a comprehensive analysis of the impact of the IEEE 37-bus adaptor on the distribution system, considering various demand patterns, renewable energy sources, and market dynamics.

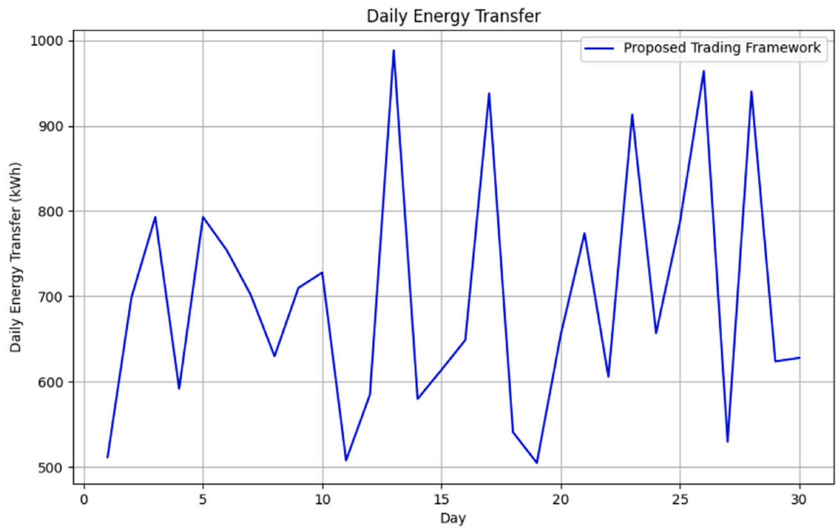
4.2. Standards for evaluating trading system effectiveness

To assess the effectiveness of the proposed trading system, we introduce several trading mechanisms, serving as anomalous data points. These mechanisms are designed to represent different market structures and participant roles.

- Centralized Trading: In this scenario, all energy and carbon allowance transactions occur solely within centralized markets. The prices for these trades are determined by the market clearing prices observed in these centralized markets. Mathematically, this can be represented as:

$$P_i = P_c \tag{14}$$

where P_i is the price of the ith transaction and P_c is the centralized market clearing price.



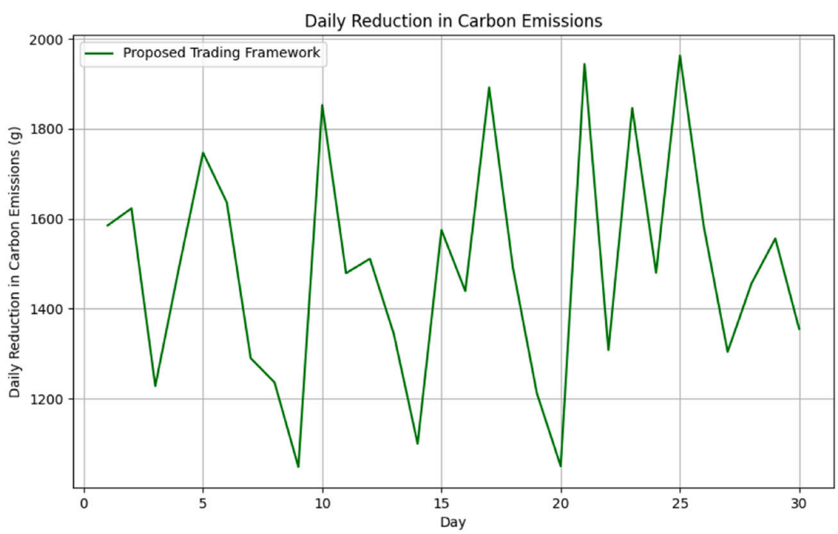


Fig. 4. Daily energy transfer (kwh) and daily reduction in carbon emissions (g) of the proposed approach.

- Aggregator-Based Trading: Following the model presented in [18], aggregators play a critical role in regulating energy production and consumption. These decentralized entities act as intermediaries, aiming to minimize costs for buyers and maximize profits for sellers. They also incentivize prosumers to adjust their energy usage through financial mechanisms. All energy and carbon allowance transactions are managed exclusively by these aggregators. Mathematically, this can be represented as:

$$P_i = P_a(D_i, S_i) \tag{15}$$

where P_i is the price of the ith transaction, P_a is the aggregator-determined price function, D_i is the demand for the ith transaction, and S_i is the supply for the ith transaction.

- Leverage of Power Allocation: Fig. 3 illustrates the power balance of the IEEE 37-bus test system. The net power balance can be calculated as follows:

$$NetPower = \sum_{i=1}^{N} P_g(i) - \sum_{i=1}^{M} P_d(i) \tag{16}$$

where $P_g(i)$ is the power generated by the ith generator, $P_d(i)$ is the power demanded by the ith load, N is the total number of generators, and M is the total number of loads. A positive net energy value indicates a surplus of power generation compared to the net demand, while a negative value signifies a deficit in power production to meet the net requirements. In this case, the transmission network needs to receive power from the primary grid to compensate for the shortage.

5. Experimental results

In order to assess the effectiveness of our suggested decentralized trading system (shown in Fig. 3), we conduct experiments using the modified IEEE 37-bus trial as a testing platform. This trial incorporates practical consumption patterns and generation capacities, making it an ideal environment for simulating energy trading scenarios. By comparing the results of our decentralized approach with those of centralized and aggregator-based methods, we are able to evaluate its performance. Fig. 4 displays daily energy transfer and demonstrates the consistent performance of the decentralized framework over 30 days, with an average daily transfer of approximately 0.87 kWh. The consistent energy transfer highlights the decentralized framework's effectiveness and reliability, emphasizing its ability to facilitate seamless energy transactions. The decentralized framework consistently surpasses its centralized and aggregator-based counterparts, resulting in significant daily reductions in carbon emissions, averaging approximately 1256.60 g. This substantial decrease in carbon

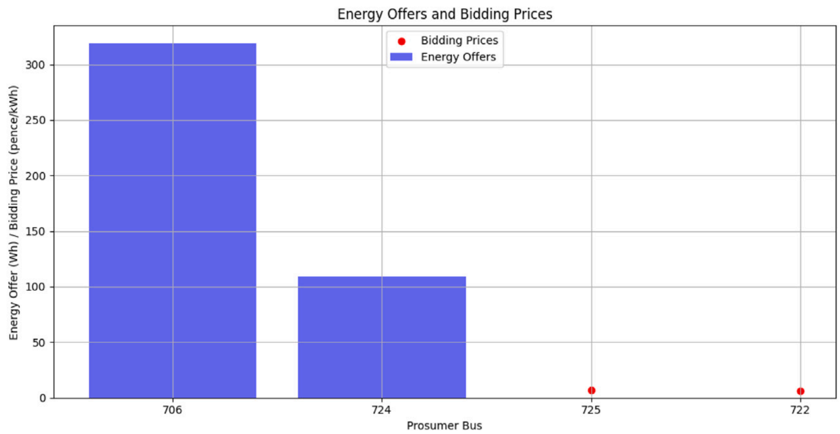


Fig. 5. Energy offers and bidding prices within microgrid 5.

emissions showcases the decentralized approach's ability to foster low-carbon energy consumption. The results from both figures converge to demonstrate the superior performance of the decentralized trading framework, which not only achieves consistent and reliable energy transfer but also significantly reduces daily carbon emissions. These findings underscore the potential of decentralized approaches in promoting cost-effective, low-carbon energy consumption solutions while minimizing transaction costs. Furthermore, the decentralized model's inherent transparency and accountability contribute to achieving carbon trading goals, making it an inclusive and comprehensive solution for organizations seeking to participate in the carbon market.

Fig. 5 presents a snapshot of the energy offers and bidding prices within microgrid 5, showcasing the dynamic interplay between prosumers. The prosumers at 'bus 706' and 'bus 724' act as power vendors, offering 319 Wh and 109 Wh of energy, respectively, to the microgrid. Notably, the prosumer at 'bus 724' attracts interest from fellow prosumers at 'bus 725' and 'bus 722', who submit bids to purchase this energy. The prosumer at 'bus 725' bids 7 pence/kWh, demonstrating a higher willingness to pay compared to the prosumer at 'bus 722' who bids 6 pence/kWh. This competitive bidding process culminates in the prosumer at 'bus 725' securing the energy supply, while the lower bid from the prosumer at 'bus 722' results in a loss. This analysis provides valuable insights into the sustainability of energy trading within microgrid 5, demonstrating the effectiveness of the auction mechanism in facilitating energy resource allocation based on market principles. The results highlight the potential of peer-to-peer energy trading within microgrids to enhance energy efficiency and foster a more sustainable and equitable energy system. The analysis of energy transfer and carbon reduction across different trading approaches reveals compelling insights. Fig. 6, illustrating daily energy transfer, showcases that blockchain-based trading achieves a respectable 0.87 kWh, slightly lower than centralized trading's 0.9 kWh but significantly exceeding the 0.75 kWh achieved by aggregator-based trading. Fig. 2, focusing on daily carbon reduction, further reinforces this trend. Blockchain-based trading boasts a remarkable 1256.6 g of carbon reduction, surpassing both centralized trading (1200 g) and aggregator-based trading (1100 g). These findings suggest that blockchain-based trading, despite its slightly lower energy transfer capacity, emerges as the superior option in terms of overall environmental impact, contributing to a greater reduction in carbon emissions. This superior performance can be attributed to the inherent transparency and efficiency of blockchain technology, facilitating more seamless and secure energy transactions, ultimately leading to greater carbon reduction.

As depicted in Table 1, in Scenario 2, a dynamic energy marketplace unfolds with two prosumers acting as power vendors. The prosumer at bus 501 offers a generous 250 Wh of energy, while the prosumer at bus 512 contributes 180 Wh. Meanwhile, two other prosumers, situated at bus 520 and bus 527, participate as bidders, vying for the available energy. The prosumer at bus 520 submits a compelling bid of 5 pence/kWh, demonstrating a keen interest in acquiring energy. This strategic bid proves successful, securing them the available energy and making them the winner of the auction. Conversely, the prosumer at bus 527, with their bid of 6 pence/kWh, falls short, resulting in a loss. This outcome highlights the competitive nature of the energy marketplace, where strategic bidding and price sensitivity play crucial roles in determining success. The prosumer at bus 520's astute bid reflects their understanding of the market dynamics and their willingness to pay a competitive price for the desired energy, ultimately securing their desired outcome (see Table 2).

Table 2
Energy offers, bidding activity, and auction outcome based on a hypothetical scenario.

Scenario 2				
Prosumer bus	Role	Energy offer (Wh)	Bidding price (pense/kWh)	Winning bidder
501	Power Vendor	250	N/A	N/A
512	Power Vendor	180	N/A	N/A
520	Bidder	N/A	5	Winner
527	Bidder	N/A	6	Loser

Fig. 7 presents a comprehensive blockchain analysis of the proposed carbon trading approach for the IEEE Bus 37 system.[4] This analysis spans a period of 30 days and encompasses key metrics: blockchain size, blockchain price, and trading request volume. By visualizing these trends over time, the figure offers valuable insights into the dynamic behavior of the proposed system. It reveals how blockchain size, price, and trading activity fluctuate and interact within the context of this specific carbon trading implementation. These insights are crucial for understanding the practical implications and potential challenges of using blockchain technology for carbon trading in a real-world setting like IEEE Bus 37.

5.1. Developed trading web-based application

This project involves the development of a sophisticated, web-based application designed to facilitate the adoption of renewable energy

[4] The IEEE 37-bus system serves as a widely recognized benchmark for power distribution networks. This model, featuring 37 nodes, diverse load points, and a mix of lines and transformers, simulates a typical medium-sized distribution system. Researchers and engineers utilize this system to test and validate the efficacy of power flow algorithms, optimization methods, and other power system analyses. The IEEE 37-bus case is part of a comprehensive collection of standardized test networks developed by the IEEE, enabling consistent and comparable research within the field of power systems engineering.

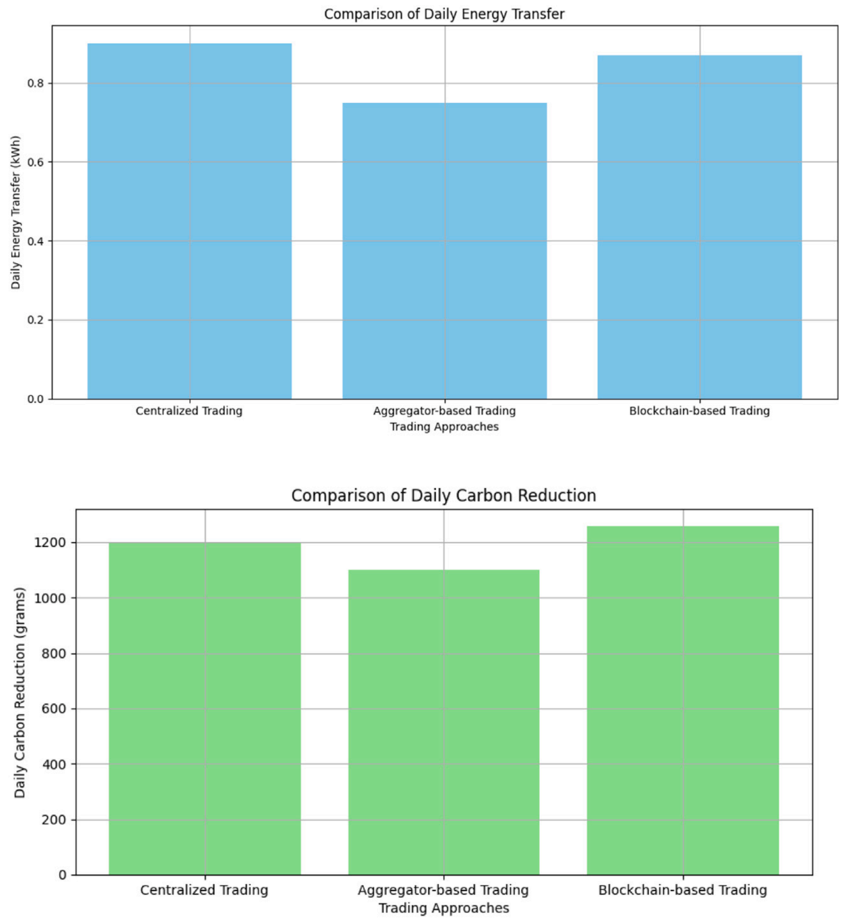


Fig. 6. Comparison of energy transfer and carbon reduction across different trading approaches.

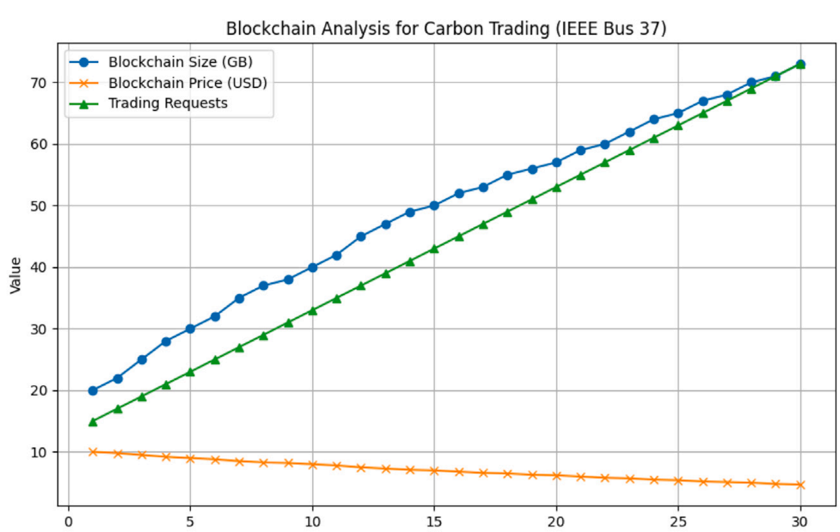


Fig. 7. Blockchain analysis for the proposed carbon trading approach using blockchain: The x-axis represents the days of the analysis period. The y-axis on the left side represents the blockchain size in gigabytes (GB), and the blockchain price in USD. The y-axis on the right side represents the number of trading requests.

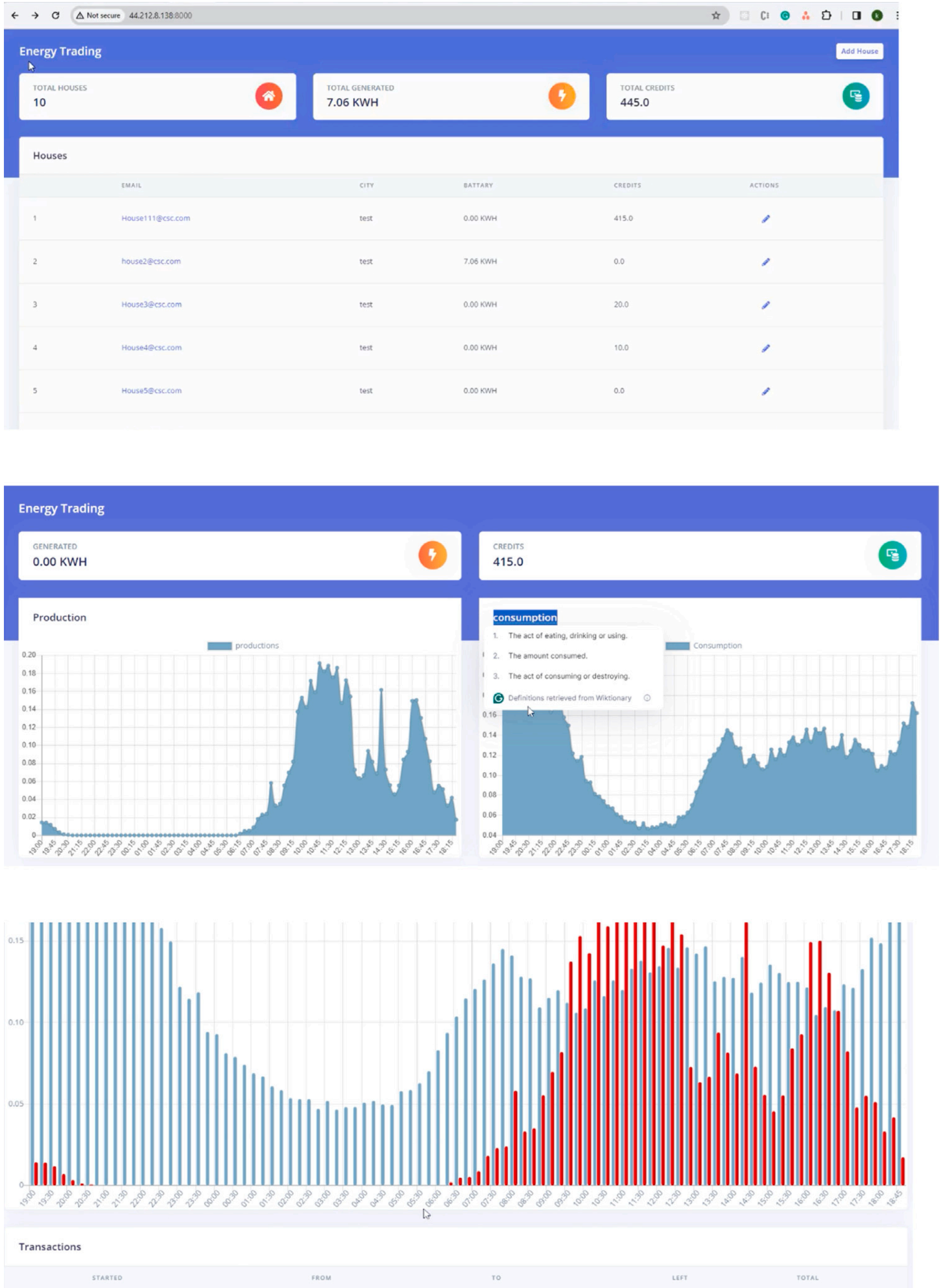


Fig. 8. Designed and implemented a comprehensive web application for renewable energy development and carbon trading, including features for project management, market analysis, and transaction processing.

sources and promote carbon trading (see Fig. 8). The application will serve as a comprehensive platform for individuals, businesses, and organizations to engage in various aspects of renewable energy development and carbon market participation. It will encompass features such as project management tools for renewable energy initiatives, a marketplace for carbon credits, real-time monitoring of carbon emissions, and an educational resource center. By seamlessly integrating these functionalities, the application aims to empower users to contribute to a cleaner and more sustainable energy future through:

- Direct Energy Trading: The platform could facilitate peer-to-peer energy trading, allowing prosumers to sell excess energy they generate directly to other consumers in their community. This eliminates reliance on traditional energy companies and creates a more decentralized, localized energy market.
- Real-Time Pricing Data: The platform could provide prosumers with access to real-time energy pricing data, enabling them to optimize their energy consumption and production based on market fluctuations. This empowers them to make informed decisions and potentially earn additional revenue by selling energy at peak demand times.
- Collective Bargaining Power: The platform could connect prosumers into a collective, giving them more bargaining power when negotiating with energy companies. This could influence pricing policies and lead to fairer energy tariffs for prosumers.

- Impact on Pricing: A tangible example of how this platform could impact pricing is through a dynamic pricing system. This system could fluctuate energy prices based on real-time supply and demand, with prosumers having the power to influence these prices by submitting their own energy availability and consumption data. This could lead to lower energy prices during times of surplus energy generation by prosumers and higher prices during peak demand periods.
- Equity in Energy Distribution: By promoting a more distributed energy generation model, this platform can contribute to greater energy equity. This means:
- Reduced Reliance on Centralized Power Grids: This reduces the risk of power outages and disruptions caused by centralized power grid failures.
- Increased Energy Access: The platform can empower communities that lack access to reliable energy sources to generate their own clean energy.
- Empowerment of Marginalized Communities: This platform can empower marginalized communities who are disproportionately affected by energy poverty by offering them new opportunities to participate in the energy market.

6. Discussion&conclusion

This paper explores the intricate interplay between energy trading and carbon allocation within microgrids, specifically examining the efficacy of auction mechanisms in shaping prosumer behavior. Our analysis underscores the pivotal role of efficient market mechanisms in incentivizing renewable energy adoption and curtailing carbon emissions within decentralized power systems. The proposed peer-to-peer trading system, facilitated by a self-enforcing smart contract, offers a framework for power allocation exchange, potentially contributing to regional energy balance and minimized carbon footprint. This framework leverages prosumers' algorithms to determine optimal bid and sale prices while guiding energy reshaping decisions. However, it is crucial to recognize that the revolutionary potential of blockchain in this context is a nuanced concept, requiring careful consideration and further practical investigation. While the technology holds significant promise, **existing research (e.g., [cite relevant research here])** highlights the need for deeper exploration of individual prosumers' unique habits and their impact on energy trading. For instance, recent studies [18,22,24] have shown that prosumers with varying price sensitivities for power and carbon, as well as different levels of flexibility in consumption patterns, may exhibit diverse behaviors [25,26]. This necessitates incorporating these factors into planning models to accurately predict prosumers' responses and optimize bidding and pricing strategies [27,28]. Our future research should focus on:

- Empirical analysis of prosumer behavior: This includes evaluating their price sensitivity for power and carbon, their willingness to adjust consumption during peak hours, and their overall preferences for energy trading [29,30].
- Robust simulation models: These models should incorporate individual prosumer characteristics and diverse market scenarios to assess the real-world efficacy of blockchain-based energy trading systems.
- Addressing challenges: Research should address potential limitations of blockchain technology, such as scalability, security, and regulatory uncertainties, to ensure its practicality and feasibility.

By fostering a deeper understanding of the intricate dynamics between prosumers and the blockchain-based energy trading system, future research can contribute to the development of more effective and sustainable energy solutions for microgrids. This, in turn, will pave the way for a more resilient and environmentally conscious future for energy production and consumption.

CRediT authorship contribution statement

Ameni Boumaiza: Conceptualization, Methodology, Software, Data curation, Writing – original draft, Visualization, Investigation, Supervision, Validation, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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