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A review of bidding strategies and energy trading models in peer-to-peer energy trading

Karibasavaraju T S,[1,2*] Kishore Kumar Pedapenki[1]

[1]*Department of Electrical and Electronics Engineering, Jain Deemed to be University, Bangalore, 562112,Karnataka, India.*
[2]*Department of Electrical and Electronics Engineering, Bapuji Institute of Engineering and Technology, Davanagere, 577004, Karnataka, India.*

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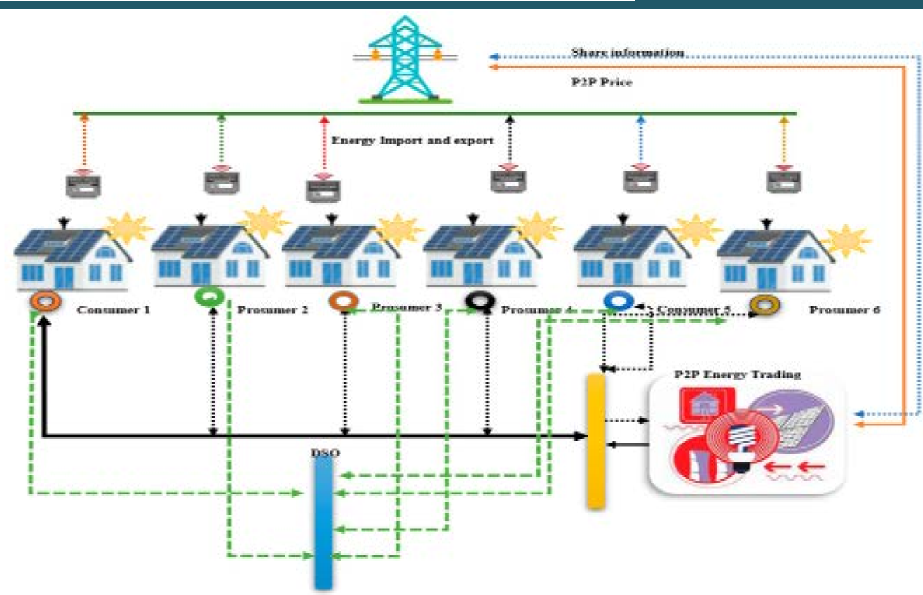
ABSTRACT



Peer-to-peer energy trading is an emerging paradigm that allows decentralized trading of energy among consumers, prosumers and other stakeholders in the energy system. This approach enables the integration of distributed energy resources and promotes energy efficiency, sustainability and consumer empowerment. This paper provides a comprehensive review of bidding strategies and energy trading models for P2P energy trading systems. Bidding strategies such as truthful bidding, strategic bidding, double-sided auctions and automated bidding are discussed, highlighting their advantages, challenges and implications for market efficiency and fairness. Additionally, various energy trading models are explored, including bilateral trading, community-based trading, block chain-based trading, centralized trading platforms and virtual power plants. The review examines the key features such as advantages and limitations of each trading model, considering factors such as the scale of the energy system, regulatory environment and the desired level of decentralization and consumer participation. The paper also highlights ongoing research efforts in developing efficient and fair bidding strategies, exploring new trading models and addressing challenges related to market design, cyber security and regulatory frameworks in P2P energy trading systems.

Keywords: Peer-to-Peer Energy Trading, Distributed Energy Resources, Bidding Strategies, Energy distribution.

INTRODUCTION

The energy sector is undergoing a profound transformation driven by the increasing adoption of distributed energy resources (DERs) such as rooftop solar panels, small-scale wind turbines, and energy storage systems. These DERs are enabling a shift from the traditional centralized energy generation and distribution model towards a more decentralized and consumer-centric paradigm. Peer-to-peer (P2P) energy trading has emerged as a promising concept that facilitates the integration of DERs into the energy market and promotes energy efficiency, sustainability and consumer empowerment.[1,2] P2P energy trading involves decentralized trading of energy among consumers, prosumers (consumers who also produce energy) and other stakeholders in the energy system. This approach allows individuals and communities to buy and sell energy directly with each other, reducing reliance on traditional energy utilities and enabling more efficient utilization of local energy resources.[3] By facilitating the exchange of energy at a local level,

*Corresponding Author: Karibasavaraju T S
Tel: 9945577364; Email: kbraju_hv@bietdvg.edu

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P2P trading has the potential to reduce transmission losses, improve grid resilience and provide economic benefits to participants. Realizing the full potential of P2P energy trading requires the development of effective bidding strategies and energy trading models. Bidding strategies determine how participants interact with the market and make decisions regarding buying or selling energy, while energy trading models define the mechanisms and platforms through which energy transactions occur.[4]

The paper aims to provide a comprehensive analysis of the current state of research in bidding strategies and energy trading models for P2P energy trading systems. It explores various bidding strategies such as truthful bidding, strategic bidding, double-sided auctions and automated bidding, evaluating their advantages, challenges and implications for market efficiency and fairness. Additionally, the paper examines different energy trading models, including bilateral trading, community-based trading, blockchain-based trading, centralized trading platforms and virtual power plants. By synthesizing the latest research findings and highlighting emerging trends, this review paper contributes to a better understanding of the key factors influencing the design and implementation of P2P energy trading systems.[5,6] it also identifies potential research gaps and opportunities for further exploration in this rapidly evolving field. As the energy landscape continues to transform, P2P energy trading has the potential to play a crucial role in enabling a more sustainable, decentralized and consumer-driven energy future.[7,8] this review paper provides a comprehensive overview of the critical components that will shape the development and adoption of this innovative approach.

BIDDING STRATEGIES

Bidding strategies play a crucial role in P2P energy trading systems, as they determine how participants interact with the market and make decisions regarding buying or selling energy. These strategies can significantly impact market efficiency, fairness and the overall performance of the trading system. This section explores various bidding strategies proposed and analyzed in the literature as shown in the Figure 1.

A. Truthful Bidding

Truthful bidding also known as sincere bidding is a strategy in which participants bid their true valuations for buying or selling energy. In other words, buyers bid the maximum price they are willing to pay and sellers bid the minimum price they are willing to accept. This approach is often considered desirable as it promotes market efficiency and fairness, as participants are not incentivized to misrepresent their preferences. Several studies have investigated the properties and implications of truthful bidding in P2P energy trading systems. The truthful bidding can lead to socially optimal outcomes under certain market conditions, such as perfect competition and complete information.[9,10]

However, truthful bidding may not always be the optimal strategy for individual participants, especially in cases where strategic behavior can lead to higher profits or lower costs. Additionally, the effectiveness of truthful bidding can be influenced by factors such as market power, information asymmetry and the presence of external incentives or regulations.

Truthful bidding also known as sincere bidding or non-strategic bidding is a strategy in which participants bid their true valuations for buying or selling energy in a P2P energy trading system. While truthful bidding is often considered a desirable approach for promoting market efficiency and fairness, there are different types or variations of truthful bidding strategies that have been explored in the literature.

Here are some of the main types of truthful bidding strategies:

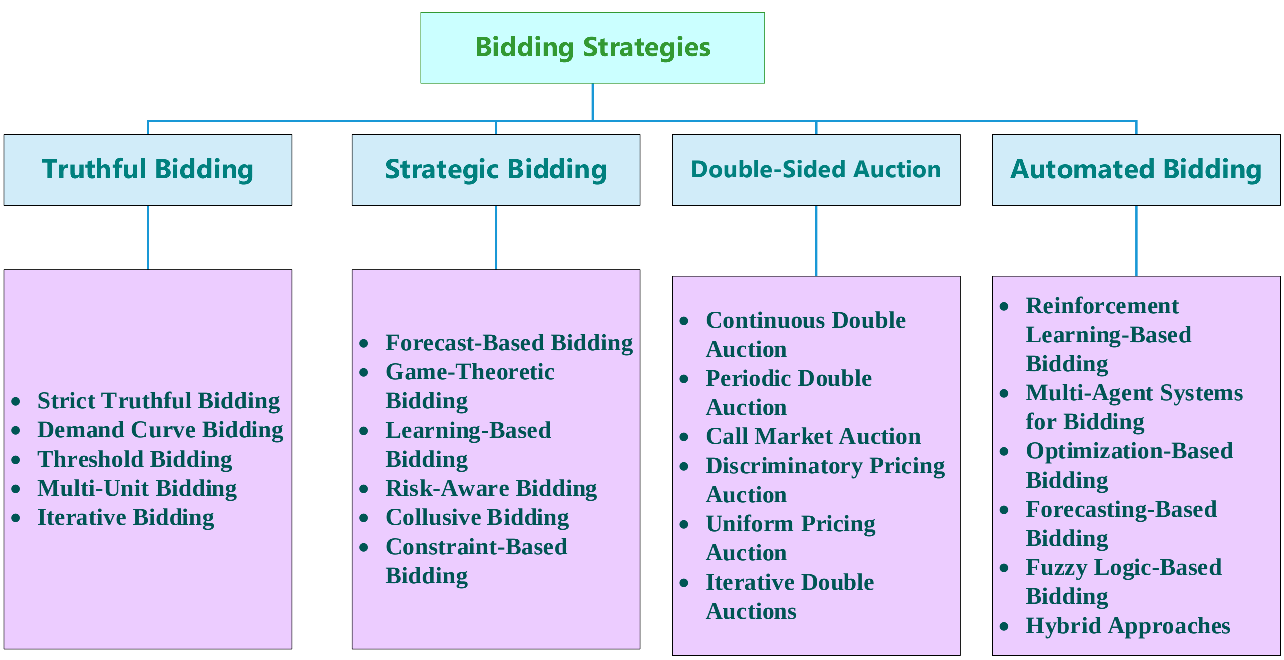

Figure 1. Different types of bidding strategies

Strict Truthful Bidding: In this approach, participants simply bid their exact true valuations without any modifications or strategic considerations. For buyers, this means bidding the maximum price they are willing to pay and for sellers, bidding the minimum price they are willing to accept. This strategy is considered the most straightforward form of truthful bidding.

Demand Curve Bidding: In demand curve bidding, buyers submit their entire demand curve as their bid, representing the quantities they are willing to purchase at different price levels. Similarly, sellers submit their supply curve, representing the quantities they are willing to sell at different prices.

This approach provides more information to the market clearing mechanism and can potentially lead to more efficient outcomes.

Threshold Bidding: Threshold bidding involves participants specifying a threshold price or quantity, above or below which they are not willing to trade. For example, a buyer may bid their true valuation along with a maximum quantity they are willing to purchase, or a seller may bid their true valuation along with a minimum quantity they are willing to sell. This strategy can help participants manage their energy demands or supply constraints.

Multi-Unit Bidding: In multi-unit bidding, participants submit bids for multiple units of energy, reflecting their true valuations for different quantities. This approach is particularly relevant in scenarios where participants have varying energy demands or supply capabilities over time or across multiple locations.

Iterative Bidding: Some truthful bidding mechanisms involve iterative processes, where participants can refine or adjust their bids over multiple rounds based on feedback from the market clearing process.

This approach can help participants better align their bids with their true valuations, especially in cases where their preferences or constraints may change over time. It's important to note that while truthful bidding strategies aim to elicit true valuations from participants, their effectiveness can be influenced by factors such as market design, information asymmetry and the presence of external incentives or regulations. Additionally, some studies have explored the potential for developing incentive-compatible mechanisms that incentivize truthful bidding as a dominant strategy for participants, even in the presence of strategic behavior.

B. Strategic Bidding

Strategic bidding involves participants using various techniques, such as forecasting, game theory and optimization algorithms to optimize their bids and maximize their profits or minimize their costs. This approach recognizes that participants may have incentives to deviate from truthful bidding in order to gain a competitive advantage in the market.[11,12] several studies have explored strategic bidding strategies in P2P energy trading systems. The bidding strategies based on machine learning techniques, such as reinforcement learning and deep learning, to predict market dynamics and adjust bids accordingly. There are several types of strategic bidding strategies that have been explored in the literature:

Forecasting-Based Bidding: In this approach, participants forecast future market conditions, such as energy prices, demand and supply, using techniques like time-series analysis, machine learning or statistical models. They then use these forecasts to optimize their bids in a way that maximizes their expected payoff. For example, sellers may bid higher prices when demand is expected to be high, and buyers may bid lower prices when supply is anticipated to be abundant.

Game-Theoretic Bidding: Game theory provides a framework for analyzing strategic interactions among participants in a market. Participants can employ game-theoretic models such as non-cooperative games or Stackelberg games to determine their optimal bidding strategies based on the anticipated behavior of other participants. This approach often involves solving for equilibrium strategies that maximize each participant's payoff given the strategies of others.

Learning-Based Bidding: Reinforcement learning and other machine learning techniques can be used to develop adaptive bidding strategies that learn from past market outcomes and adjust bids accordingly. These strategies can be particularly useful in dynamic and uncertain environments, where market conditions may change over time.

Risk-Aware Bidding: Participants may incorporate risk considerations into their bidding strategies by accounting for factors such as price volatility, supply uncertainty or the risk of not being able to meet their energy demands or commitments. Risk-aware bidding strategies can involve techniques like stochastic optimization, robust optimization or risk-constrained optimization.

Collusive Bidding: In some cases, participants may engage in collusive behavior, where they coordinate their bidding strategies to manipulate market prices or allocations in their favor. This type of strategic bidding can undermine market efficiency and fairness and is often discouraged or prohibited by market regulations

Constraint-Based Bidding: Participants may have various constraints, such as energy generation or storage capacities, load requirements or budget limitations that need to be considered in their bidding strategies. Constraint-based bidding strategies aim to optimize bids while ensuring that these constraints are satisfied.

The choice of strategic bidding strategy depends on factors such as the market design, participant objectives, computational capabilities and the availability of information and forecasting tools. It's important to note that while strategic bidding can potentially lead to higher individual payoffs, it may also result in market inefficiencies and unfair outcomes, if participants have significant market power or engage in collusive behavior. Appropriate market mechanisms and regulations may be necessary to mitigate the negative impacts of strategic bidding.

C. Double-Sided Auction Bidding

Double-sided auction bidding is a strategy often employed in P2P energy trading systems where both buyers and sellers submit their bids and offers simultaneously. A market clearing mechanism is then used to determine the traded energy and prices based on the submitted bids and offers .[13,14,15]

Several studies have investigated the application of double-sided auctions in P2P energy trading systems have proposed auction mechanisms that aim to achieve desirable properties such as allocative efficiency, budget balance and incentive compatibility. These mechanisms often involve iterative bidding processes and sophisticated clearing algorithms to match buyers and sellers effectively.

One advantage of double-sided auction bidding is that it can facilitate decentralized and real- time energy trading, enabling participants to respond to changing market conditions and energy demands. However, the complexity of the auction mechanisms and the potential for strategic behavior can pose challenges in terms of computational requirements, market transparency and fairness. There are several types of double-sided auction bidding mechanisms that have been explored in the literature:

Continuous Double Auction (CDA): In a continuous double auction, buyers and sellers can submit bids and offers at any time and trades are executed whenever a buyer's bid meets or exceeds a seller's offer. This mechanism allows for continuous and real-time trading, similar to behavior of traditional stock exchanges. CDA are often used in P2P energy trading systems with a large number of participants and frequent trading activities.

Periodic Double Auction: In a periodic double auction, trading occurs at specific time intervals, such as hourly or daily. Participants submit their bids and offers within a fixed bidding window and a market clearing mechanism is executed at the end of the bidding period to determine the traded energy and prices. This approach is suitable for scenarios where energy trading occurs at predetermined intervals or when computational resources are limited.

Call Market Auction: A call market auction is a type of periodic double auction where all bids and offers are collected during a specific bidding period and trades are executed simultaneously at a single clearing price. This mechanism ensures that all trades are executed at the same price, which can promote fairness and transparency. Call market auctions are often used in energy markets with a large number of participants and high trading volumes.

Discriminatory Pricing Auction: In a discriminatory pricing auction, trades are executed at the bid or offer prices submitted by the participants. This means that buyers may pay different prices for the same quantity of energy and sellers may receive different prices for the same quantity sold. While this approach can incentivize truthful bidding, it may lead to less efficient market outcomes compared to uniform pricing mechanisms

Uniform Pricing Auction: In a uniform pricing auction, all trades are executed at a single clearing price, determined by the intersection of the aggregate demand and supply curves. This mechanism ensures that all buyers pay the same price for the same quantity of energy and all sellers receive the same price for the same quantity sold. Uniform pricing auctions are often preferred for their fairness and efficiency properties.

Iterative Double Auctions: Iterative double auctions involve multiple rounds of bidding, where participants can adjust their bids and offers based on feedback from previous rounds. This approach can help participants refine their valuations and converge towards an equilibrium price. Iterative double auctions can be designed with different termination criteria, such as a maximum number of rounds or a convergence threshold.

The choice of double-sided auction bidding mechanism depends on factors such as the market design, computational resources, desired properties, characteristics of the participants and trading activities. Some mechanisms may be more suitable for real-time trading, while others may be better suited for periodic or call market settings. Additionally, the design of the auction mechanism should consider potential issues such as market power, collusion and the presence of strategic bidding behavior.

D. Automated Bidding

Automated bidding involves the use of machine learning and optimization algorithms to automate the bidding process based on various factors, such as energy demand, supply and prices. This approach can help reduce the cognitive burden on participants and enable more efficient and responsive bidding strategies.[16]

Several studies have explored automated bidding strategies in P2P energy trading systems. Have proposed techniques such as reinforcement learning, multi-agent systems and evolutionary algorithms to develop bidding strategies that adapt to changing market conditions and optimize participant objectives.

Automated bidding can be particularly useful in scenarios where real-time decision-making is required, such as in response to fluctuations in renewable energy generation or changes in energy demand. However, the effectiveness of automated bidding strategies relies heavily on the quality and reliability of the underlying data and algorithms, as well as the ability to accurately model participant preferences and market dynamics.

The choice of bidding strategy in P2P energy trading systems depends on various factors, such as market design, participant objectives, computational capabilities and the desired trade-offs between efficiency, fairness and individual payoffs. It is important to carefully evaluate the strengths and limitations of each strategy and consider the potential implications for market outcomes and participant behavior. There are several types of automated bidding strategies that have been explored in the literature:

Reinforcement Learning-Based Bidding: Reinforcement learning algorithms, such as Q-learning, deep Q-networks and policy gradient methods can be used to develop automated bidding strategies that learn from past market outcomes and adapt their bidding behavior accordingly. These algorithms aim to maximize a predefined reward function, which can be based on factors like profits, energy balancing or user preferences.

Multi-Agent Systems for Bidding: Multi-agent systems involve multiple autonomous agents each representing a participant in the P2P energy trading system. These agents can use various techniques such as game theory, evolutionary algorithms or negotiation protocols to determine their bidding strategies while considering the actions and objectives of other agents.

Optimization-Based Bidding: Optimization algorithms such as linear programming, mixed-integer programming or stochastic optimization can be used to develop automated bidding strategies that optimize participant objectives subject to various constraints. These constraints may include energy demand, supply, storage capacities, budget limitations or risk preferences.

Forecasting-Based Bidding: Automated bidding strategies can incorporate forecasting techniques to predict future market conditions such as energy prices, demand and supply. These forecasts can then be used to optimize bids accordingly. Techniques like time-series analysis, machine learning models such as neural networks, support vector machines and ensemble methods can be employed for forecasting.

Fuzzy Logic-Based Bidding: Fuzzy logic systems can be used to develop automated bidding strategies that handle uncertainty and imprecision in participant preferences, market conditions, or energy data. These systems use fuzzy rules and membership functions to map inputs (energy demand, prices) to outputs (bid quantities, bid prices).

Hybrid Approaches: Some automated bidding strategies combine multiple techniques, such as reinforcement learning with optimization algorithms, or fuzzy logic with forecasting models. These hybrid approaches aim to leverage the strengths of different methods to improve the performance and adaptability of the bidding strategies. The choice of automated bidding strategy depends on factors such as the complexity of the P2P energy trading system, the availability of data and computational resources, the desired properties (e.g., adaptability, scalability, interpretability), and the specific objectives and constraints of the participants. Additionally, the effectiveness of automated bidding strategies relies on the quality and reliability of the underlying data, algorithms, and models used for decision-making.

It's important to note that while automated bidding can help reduce the cognitive burden on participants and enable more efficient and responsive bidding, it also introduces challenges related to algorithm transparency, fairness and potential biases or vulnerabilities in the decision-making process. Appropriate measures, such as algorithm auditing, testing and monitoring, may be necessary to ensure the responsible and ethical deployment of automated bidding strategies.

To bridge the discussion from bidding tactics to energy trading models, the pivotal role of bidding strategies in shaping the dynamics of P2P energy markets must be considered. Bidding tactics form the foundation for participants to negotiate energy prices and allocate resources efficiently within decentralized networks. However, these strategies operate within a broader framework of energy trading models that define the structural and functional mechanisms of these markets. Examining how bidding tactics integrate with and influence various energy trading models such as auction-based, bilateral or blockchain enabled frameworks provides a clearer understanding of their impact on market efficiency, participant engagement and overall system optimization.

ENERGY TRADING MODELS

An Energy Trading Model refers to the framework or platform that defines the mechanisms and rules for buying and selling energy among participants in a peer-to-peer (P2P) energy trading system.[17,18,19]

It specifies the underlying architecture, market structure and protocols that govern the interactions and transactions between energy producers, consumers, prosumers and other stakeholders involved in the decentralized energy trading process.

Key components of an Energy Trading Model include:

Market participants: This defines the entities involved in the trading process, such as individual households, communities, microgrids or virtual power plants (aggregators of distributed energy resources).

Trading platform: This refers to the physical or virtual marketplace where energy trading occurs, which can be a centralized platform, a decentralized blockchain- based system or a community-based trading network.

Transaction mechanisms: This describes the process by which energy is bought and sold, such as through bilateral contracts, auctions, continuous double auctions, or other market clearing mechanisms

Pricing and settlement: The model specify how energy prices are determined such as based on supply, demand, negotiated prices or fixed tariffs and how financial settlements are conducted for energy transactions.

Regulatory and policy framework: The trading model must operate within the boundaries of relevant regulations, policies and standards governing the energy sector, such as grid interconnection rules, consumer protection laws and data privacy requirements.

Information and communication infrastructure: The model defines the technology and protocols for exchanging energy data, bids, offers and other information among participants, such as smart meters, blockchain networks or centralized databases.

The Energy Trading Model plays a crucial role in enabling and shaping the decentralized energy market, influencing factors such as market efficiency, fairness, transparency and the level of consumer participation and empowerment. Different models may be more suitable for specific contexts, depending on factors like the scale of the energy system, the regulatory environment and the desired level of decentralization and consumer participation.[20,21]

P2P energy trading can be facilitated through various trading models, each with its own advantages, challenges and underlying mechanisms. These models define the platform and mechanisms through which energy transactions occur among participants in the P2P energy trading system. In this section, explores several prominent energy trading models that have been proposed and analyzed in the literature as shown in the Figure 2.

A. Bilateral Trading

In the bilateral trading model, energy is traded directly between two parties (a prosumer and a consumer) through negotiations or predefined contracts. This model allows for direct peer- to-peer transactions without the need for a centralized intermediary or market operator.

Several studies have investigated bilateral trading models for P2P energy trading systems have proposed frameworks for negotiating bilateral contracts, where participants can exchange offers and counteroffers until an agreement is reached. Khorasany et al. (2019)[22] proposed a decentralized bilateral energy trading system for peer-to-peer electricity markets.

One advantage of bilateral trading is its simplicity and flexibility, as it allows participants to tailor their transactions based on their specific needs and preferences. However, this model can be challenging to scale to larger systems with many participants, as it requires managing multiple bilateral relationships and negotiations. Additionally, ensuring fair and efficient outcomes in bilateral trading may require robust mechanisms to address issues such as market power imbalances and information asymmetries. There are several types of bilateral trading that have been explored in the literature:

Negotiated bilateral contracts: In this type of bilateral trading, buyers and sellers engage in a negotiation process to determine the terms of the energy trade, such as the quantity, price and duration. Various negotiation protocols and strategies can be employed, including game-theoretic approaches, multi-agent negotiation and iterative bargaining processes.

Fixed-price bilateral contracts: In this model, the energy price is fixed in advance and buyers and sellers agree to trade energy at that predetermined price. The fixed price can be based on factors such as market conditions, historical data or regulated tariffs.

Time-of-use bilateral contracts: These contracts involve different energy prices for different time periods, reflecting the varying costs and demand patterns throughout the day or week. For example, prices may be higher during peak demand hours and lower during off-peak hours.

Subscription-based bilateral trading: In this model, consumers subscribe to a specific energy producer or prosumer for a fixed period, agreeing to purchase a predetermined amount of energy at a predefined price or pricing scheme.

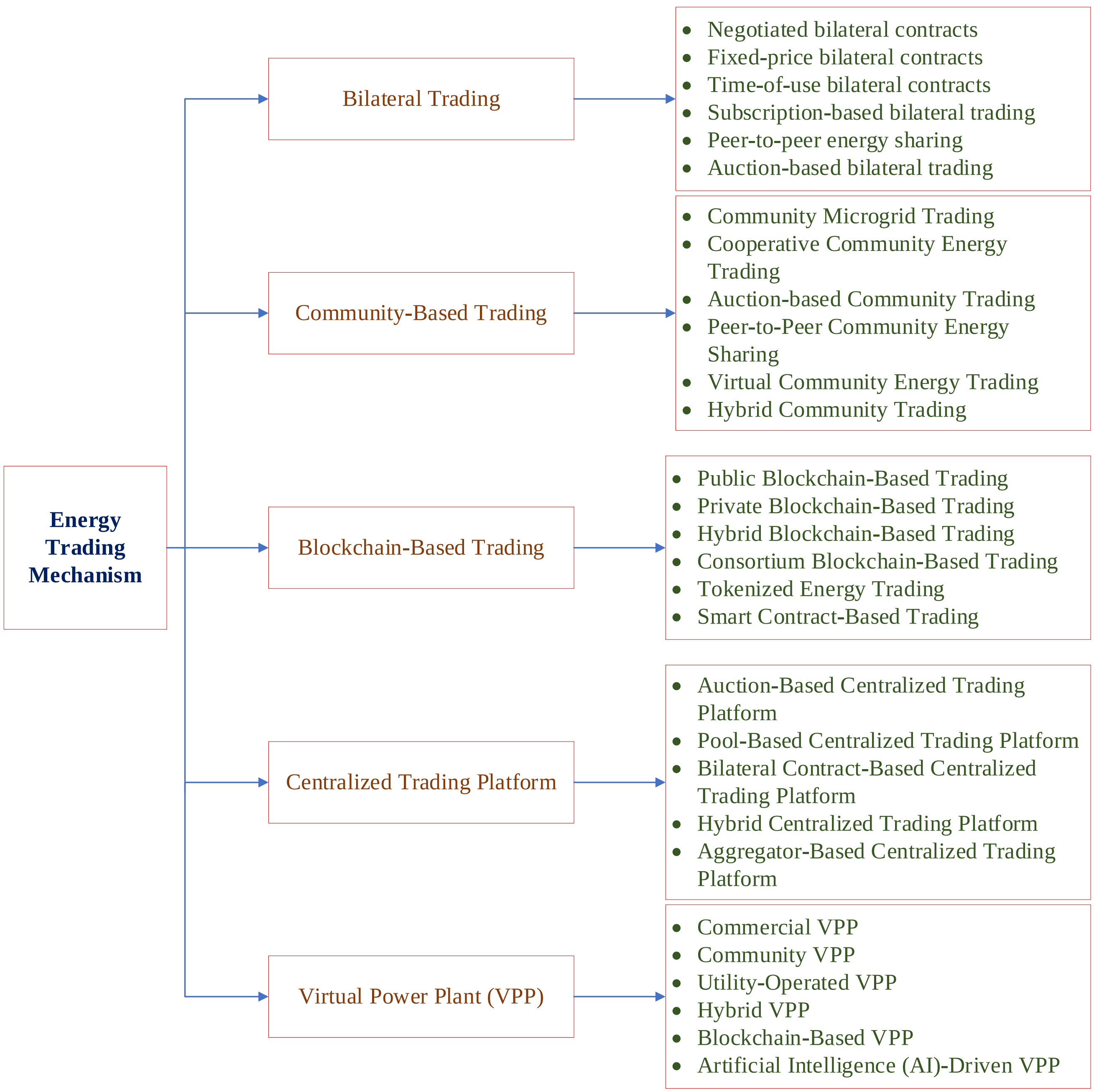

Figure 2. Different types of energy trading mechanisms

Peer-to-peer energy sharing: This type of bilateral trading involves energy sharing among peers, often within a local community or microgrid. It can be based on cooperative agreements, where participants share their surplus energy without explicit pricing or with a predefined compensation mechanism.

Auction-based bilateral trading: In this approach, buyers and sellers participate in an auction process to negotiate and determine the bilateral trade. Various auction formats, such as double auctions or continuous double auctions can be used to facilitate the bidding and matching process.

The choice of bilateral trading type depends on factors such as the market design, regulatory framework, participant preferences and the level of decentralization and consumer engagement desired. Some bilateral trading models may be more suitable for small-scale, local trading, while others may be better suited for larger-scale or more dynamic energy markets. Additionally, bilateral trading can be combined with other energy trading models, such as community-based trading or virtual power plant models to create hybrid approaches.

B. Community-Based Trading

Community-based trading models focus on enabling energy trading within a local community or microgrid. In these models, participants can buy and sell energy among themselves, leveraging local energy resources and reducing reliance on the main grid.[23]

Several studies have explored community-based trading models for P2P energy trading systems. Auction-based mechanisms for community energy trading, where participants submit bids and offers and a community energy manager determines the traded energy and prices have proposed in Manjunatha, H. M et al. (2023)[24]. Muhsen et.al. (2022)[25] have investigated cooperative game-theoretic approaches, where participants collaborate to achieve collective objectives, such as maximizing community welfare or minimizing energy costs.

Community-based trading models can promote energy self-sufficiency, resilience and local economic benefits. However, they may face challenges related to balancing local energy supply and demand, managing grid constraints and ensuring fair and efficient allocation of energy resources within the community. Several types of community-based trading models have been proposed and explored in the literature:

Community Microgrid Trading: In this model, a local microgrid serves as the platform for energy trading among community members. The microgrid may consist of distributed energy resources (DERs) such as rooftop solar panels, small wind turbines and energy storage systems owned by individual prosumers or the community. A community energy manager or controller coordinates the trading activities within the microgrid.

Cooperative Community Energy Trading: This model is based on cooperative game theory principles, where community members collaborate to achieve collective objectives, such as maximizing community welfare or minimizing overall energy costs. Participants agree to share their energy resources and make collective decisions on energy production, consumption and trading strategies.

Auction-based Community Trading: In this approach, community members participate in auctions to buy and sell energy within the community. Various auction mechanisms, such as double auctions or continuous double auctions, can be employed. A community energy manager or platform acts as the auctioneer, facilitating the bidding and matching process.

Peer-to-Peer Community Energy Sharing: This model involves direct peer-to-peer energy sharing among community members, often without explicit pricing or with a predefined compensation mechanism. It is based on cooperation and the sharing of surplus energy within the community, promoting energy self- sufficiency and local resilience.

Virtual Community Energy Trading: In this model, a virtual community is formed, where participants may not necessarily be physically connected but can trade energy virtually through a digital platform or blockchain- based system. This approach can enable energy trading across larger geographical areas while maintaining the community-based principles.

Hybrid Community Trading: Some models combine elements of different community-based trading approaches, such as cooperative decision-making with auction-based mechanisms or virtual trading with physical microgrids. These hybrid models aim to leverage the advantages of multiple approaches while addressing their respective limitations.

The choice of community-based trading model depends on factors such as the size and characteristics of the community, the available energy resources, the desired level of decentralization and consumer participation and the regulatory and policy environment. Additionally, community-based trading models may be integrated with other energy trading models, such as virtual power plants or centralized trading platforms, to create more comprehensive and flexible energy trading ecosystems.

C. Blockchain-Based Trading

Blockchain technology has been proposed as a decentralized platform for enabling secure and transparent P2P energy trading. In blockchain-based trading models, energy transactions are recorded on a distributed ledger, eliminating the need for a centralized intermediary and enabling real-time and peer-to-peer transactions.

Several studies have explored the use of blockchain technology for P2P energy trading systems. Blockchain-based architectures and protocols for energy trading, addressing issues such as transaction validation, consensus mechanisms and smart contract implementation have proposed by Karumba et al. (2023)[26]. Samuel et al. (2021)[27] demonstrated a secure blockchain-based demurrage mechanism for energy trading in smart communities.

Blockchain-based trading models offer several potential benefits, including increased transparency, security and decentralization. However, they also face challenges related to scalability, energy consumption and regulatory compliance. Additionally, the adoption of blockchain technology in energy trading systems may require overcoming technical and regulatory barriers as well as ensuring interoperability with existing energy infrastructure and systems.

Block chain technology has been proposed as a decentralized platform for enabling secure and transparent peer-to-peer (P2P) energy trading. Several types of blockchain-based trading models have been explored in the literature:

Public Blockchain-Based Trading: In this model, a public blockchain network, such as Ethereum or Bitcoin is used as the platform for P2P energy trading. Transactions are recorded on the distributed ledger and consensus mechanisms like proof-of-work or proof-of-stake are employed to validate and secure the transactions. This approach ensures transparency, immutability and decentralization, but may face scalability and energy consumption challenges.

Private/Permissioned Blockchain-Based Trading: Unlike public blockchains, private or permissioned blockchains are controlled by a consortium or a single entity, with restricted access and participation. In the context of energy trading, a utility, microgrid operator or energy community manager may establish a private blockchain network for secure and efficient P2P energy trading among authorized participants.

Hybrid Blockchain-Based Trading: Hybrid models combine elements of public and private blockchains to leverage their respective advantages. For example, a private blockchain may be used for internal energy trading within a community or microgrid, while a public blockchain facilitates inter- community or external energy trading, ensuring transparency and leveraging the computational power of public networks.

Consortium Blockchain-Based Trading: In this model, a consortium of energy stakeholders, such as utilities, regulatory bodies and consumer groups, jointly establish and maintain a blockchain network for P2P energy trading. The consortium members share the responsibility of validating transactions and managing the network, promoting trust, transparency and collaboration among participants.

Tokenized Energy Trading: Some blockchain-based trading models involve the use of tokenized energy assets or cryptocurrencies. Energy producers can tokenize their energy output and trade these tokens directly with consumers or prosumers on blockchain-based energy trading platforms. This approach can facilitate micropayments and enable new business models in the energy sector.

Smart Contract-Based Trading: Smart contracts, which are self-executing programs on the blockchain can be used to automate and enforce the rules and conditions of energy trading agreements. Smart contracts can handle various aspects of the trading process such as bid matching, pricing, settlement,grid constraints and ensuring transparency and also reducing the need for intermediaries.

The choice of blockchain-based trading model depends on factors such as the desired level of decentralization, scalability requirements, regulatory constraints and the specific objectives and constraints of the energy trading participants. Additionally, blockchain-based trading models may be integrated with other technologies such as Internet of Things (IoT) devices and machine learning algorithms to enhance the functionality and intelligence of the energy trading ecosystem.

D. Centralized Trading Platform

In the centralized trading platform model, a central entity such as a utility or market operator, manages the trading platform and facilitates transactions among participants in the P2P energy trading system. This model provides a centralized marketplace for energy trading, similar to traditional energy markets.

Several studies have investigated centralized trading platforms for P2P energy trading systems. Hamouda et al. (2021) [28] have proposed auction-based mechanisms, where participants submit bids and offers to the central platform, and a market clearing algorithm determines the traded energy and prices. The other authors Jiang et al. (2020) [29] and Liu et al. (2021) [30] have explored the use of optimization techniques and game - theoretic models to design centralized trading platforms that achieve desirable outcomes, such as maximizing social welfare or minimizing energy costs.

Centralized trading platforms offer the advantages of centralized coordination, market oversight and the potential for efficient resource allocation. However, they may face challenges related to ensuring fair and transparent operations, addressing potential conflicts of interest and maintaining the trust and participation of decentralized energy resources and prosumers. Several types of centralized trading platforms have been proposed and studied:

Auction-Based Centralized Trading Platform: This type of platform employs auction mechanisms to facilitate energy trading. Participants submit bids and offers to the central platform and a market clearing algorithm determines the traded energy and prices. Different auction formats can be used such as double auctions, continuous double auctions or call auctions.

Pool-Based Centralized Trading Platform: In this model, participants pool their energy resources and the central platform manages the allocation and distribution of energy within the pool. The platform uses optimization algorithms to maximize objectives such as social welfare or minimize energy costs while considering various constraints.

Bilateral Contract-Based Centralized Trading Platform: This platform facilitates bilateral contracts between buyers and sellers, acting as an intermediary and providing a centralized marketplace. Participants can negotiate and agree on bilateral contracts, which are then managed and settled by the central platform.

Hybrid Centralized Trading Platform: Some platforms combine elements of different trading mechanisms, such as auctions, bilateral contracts and pool-based trading to create a hybrid model. This approach aims to leverage the advantages of multiple mechanisms while addressing their respective limitations.

Aggregator-Based Centralized Trading Platform: In this model, the central platform acts as an aggregator, pooling and optimizing the operation of distributed energy resources (DERs) and representing them as a single entity in energy markets. The platform manages the trading activities of the aggregated DERs, enabling their participation in both wholesale and retail energy markets.

Integrated Centralized Trading Platform: These platforms integrate energy trading with other energy services and functionalities such as demand response, virtual power plants and grid ancillary services. The central platform acts as a comprehensive energy management system, coordinating various aspects of the energy system while facilitating P2P energy trading.

The choice of centralized trading platform model depends on factors such as the scale of the energy system, the desired level of centralized control and coordination, the regulatory environment and the specific objectives and constraints of the participants. Centralized platforms may offer advantages in terms of market oversight, efficient resource allocation, and the potential for integrating additional energy services. However, they may also face challenges related to ensuring fair and transparent operations, addressing potential conflicts of interest and maintaining the trust and participation of decentralized energy resources and prosumers.

E. Virtual Power Plant (VPP)

A Virtual Power Plant (VPP) is an energy trading model that aggregates and optimizes the operation of distributed energy resources, enabling them to participate in energy markets as a single entity. In a VPP, an aggregator coordinates and manages a portfolio of DERs such as rooftop solar panels, small-scale wind turbines and energy storage systems to provide energy services and participate in energy trading.

Several studies have explored the use of VPPs in P2P energy trading systems. The author Manjunatha, H. M et al. (2021)[31] have proposed optimization models and control strategies for VPPs aiming to maximize the economic benefits and operational efficiency of the aggregated DERs. Manjunatha, H.M et al.(2021)[32] have investigated the integration of VPPs with energy trading platforms, enabling the participation of DERs in both wholesale and retail energy markets.

VPPs can facilitate the integration of distributed energy resources into energy markets, unlocking their potential for providing grid services and energy trading. However, challenges may arise in terms of ensuring fair compensation for DER owners, managing operational constraints and uncertainties, and addressing potential conflicts of interest between the aggregator and individual DER owners. Several types of VPP models have been explored in the literature:

Commercial VPP: In this model, an aggregator or a third-party entity creates a portfolio of DERs, such as rooftop solar panels, small wind turbines and energy storage systems, which is owned by residential or commercial customers. The aggregator manages and optimizes the operation of these DERs to provide energy services and participate in energy markets, while compensating the DER owners for their contributions.

Community VPP: A community VPP involves the aggregation and coordination of DERs within a local community or microgrid. The VPP is owned and managed by the community itself or a community energy cooperative, promoting energy self-sufficiency, resilience and local economic benefits.

Utility-Operated VPP: In this model, a utility company or a distribution system operator (DSO) act as the aggregator creating a VPP by coordinating and optimizing the operation of DERs connected to their distribution network. The utility-operated VPP can participate in wholesale energy markets, provide grid services and facilitate the integration of distributed resources [33].

Hybrid VPP: Hybrid VPP models combine elements of different VPP types such as commercial and community-based VPPs or utility-operated and third-party VPPs. This approach aims to leverage the advantages of multiple models while addressing their respective limitations.

Blockchain-Based VPP: Some VPP models incorporate blockchain technology to enable decentralized and transparent coordination of DERs. In this approach, DER owners and other stakeholders can participate in a blockchain-based platform, where smart contracts automate the aggregation, optimization and trading of energy resources within the VPP.

Artificial Intelligence (AI)-Driven VPP: AI techniques, such as machine learning, optimization algorithms, and multi-agent systems, can be employed to enhance the functionality and decision-making capabilities of VPPs. AI- driven VPPs can optimize the operation of DERs in real-time, adapt to changing market conditions and provide advanced forecasting and control capabilities.

The choice of VPP model depends on factors such as the scale and distribution of DERs, the regulatory environment, the desired level of centralization or decentralization, and the specific objectives and constraints of the participants. VPPs can facilitate the integration of distributed resources into energy markets, unlocking their potential for providing grid services and energy trading. However, challenges may arise in terms of ensuring fair compensation for DER owners, managing operational constraints and uncertainties and addressing potential conflicts of interest between aggregators and individual DER owners.

The choice of energy trading model depends on various factors, such as the scale of the energy system, the regulatory environment, the desired level of decentralization and consumer participation and the specific objectives and also constraints of the participants. Some models may be more suitable for local or community-based trading, while others may be better suited for larger-scale or centralized energy markets. Additionally, hybrid models that combine elements of different trading models may be explored to leverage the advantages of multiple approaches.

As P2P energy trading systems continue to evolve, ongoing research efforts are focused on developing efficient and robust trading models, addressing challenges related to market design, cyber security and regulatory frameworks, and ensuring the seamless integration of distributed energy resources into the energy landscape.

Case Studies

A. Case Study-1: Transitioning to an Auction-Based Single-Sided Bidding Electricity Market in a Grid-Tied Microgrid

H.M. Manjunatha et al. (2024)[15] proposed an auction-based single-sided bidding electricity market as an alternative to the bilateral contractual energy trading model in a grid-tied microgrid. The study explores the replacement of the traditional bilateral contractual energy trading model with an auction-based single-sided bidding electricity market (SSAM) in a grid-tied microgrid (MG). The bilateral model relies on fixed prices and pre-arranged agreements, often failing to address real-time supply-demand mismatches. The Malnad College of Engineering (MCE) campus microgrid in Hassan, Karnataka, India, served as the case study's testbed, integrating a 120 kW solar photovoltaic (SPV) system. The case study's testbed is shown in Figure 3.

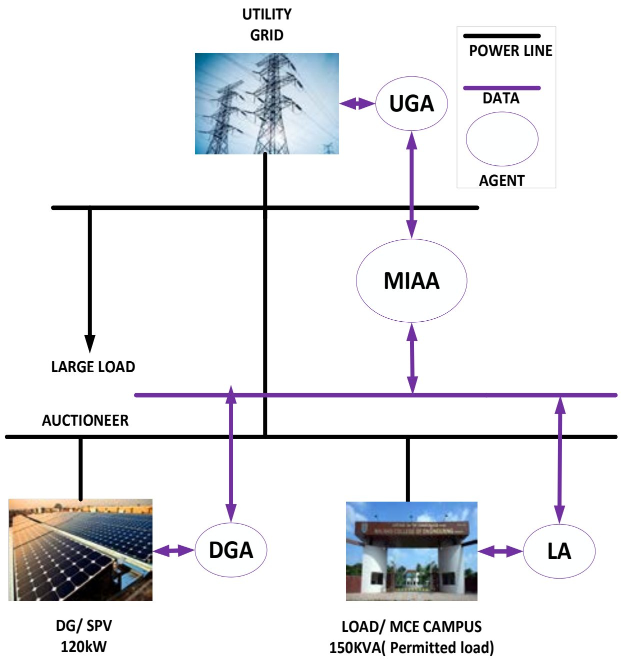

Figure 3. MCE Grid-tied MG

The primary objective was to enhance profit-sharing among stakeholders and improve market efficiency. To achieve this, two novel bidding algorithms were developed. The Linear Bidding Algorithm (LBA) calculates the seller's "ask price" (A_{PS}) using a linear function based on generation capacity. The formula for APS is given as:

$$AP_S - G_{bp} = \frac{(W_{lp}^g - G_{bp})}{(S_{RC} - 0.5S_{RC})}(P_S - 0.5S_{RC}) \quad (1)$$

where G_{bp} is the quoted grid buying price, W^g_{lp} is the weighted average of grid limiting prices, S_{RC} is the rated capacity of SPV, and P_S is the power generation of the SPV.

The Fuzzy Logic-Based Bidding Algorithm (FLBA) incorporates supply-demand mismatch into the bidding mechanism using the Generation Difference Factor (GDF):

$$\Delta P = \frac{P_S}{T_{MCE}^l} \quad (2)$$

$$\begin{Bmatrix} \boldsymbol{IF}(T_{MCE}^l \ is\ > P_S) \\ GDF = \frac{(T_{MCE}^l - P_S)}{P_S} \\ \boldsymbol{IF}(T_{MCE}^l \ is\ \leq P_S) \\ GDF = 0 \end{Bmatrix} \quad (3)$$

$$AP_S - G_{bp} = \frac{(W_{lp}^g - G_{bp})}{(1 - 0.5)}(CF - 0.5) \quad (4)$$

Where T^l_{MCE} is the total load demand of the MCE campus. The GDF adjusts the A_{PS} dynamically, making it dependent on real-time mismatches.

A multi-agent system (MAS) coordinated real-time communication and decision-making between agents representing the SPV (DGA), the MCE campus load (LA), the utility grid (UGA), and the microgrid intelligent aggregator (MIAA). The MIAA used these inputs to calculate the Market Clearing Prices (MCP) based on equations such as:

$$MCP = A_{PS} + \frac{[(1 + (1 - \Delta P))\ X\ A_{PS}]}{2} \quad (5)$$

where ΔP represents the supply-demand mismatch.

Simulations revealed significant improvements with SSAM. Under the bilateral model, the MCE campus achieved low electricity costs, but SPV sellers had limited profit margins. The SSAM model, particularly with FLBA, significantly boosted sellers' profits while keeping costs competitive for buyers. During surplus and deficit periods, market-clearing prices dynamically adjusted, ensuring ethical trading and fairness. For instance, the SPV sellers' profit margins were highest when using FLBA, as it considered both power generation variations and supply-demand mismatches.

Economic analysis demonstrated that FLBA-based SSAM increased SPV seller profits while optimizing costs for the MCE campus. Moreover, the dynamic pricing strategies improved overall market efficiency by promoting fair and transparent transactions.

The SSAM model, leveraging LBA and FLBA, represents a compelling alternative to traditional bilateral trading. By aligning stakeholder incentives, it creates a sustainable and adaptive energy market. This case study illustrates how intelligent systems and advanced bidding strategies can transform energy trading in microgrids.

B. Case Study-2: Blockchain-Based Energy Trading Platform

Kumari et. al.(2019)[34] presented the development and implementation of a blockchain-based energy trading platform leveraging Hyperledger Composer Rest Server. This platform is designed to enable secure P2P energy trading, addressing key challenges such as reliance on third parties, transaction security, and trust in decentralized energy markets. By integrating Distributed Energy Resources (DER), the platform aims to enhance transparency and efficiency in energy transactions while providing a robust and decentralized architecture.

The primary objective of the platform is to establish a decentralized system that ensures secure authentication of participants or prosumers using blockchain technology. Prosumers both producers and consumers of energy are given unique digital IDs stored on an immutable blockchain ledger. This setup eliminates the need for intermediaries, enabling direct energy trading between participants. Additionally, the system provides real-time access to transaction histories, ensuring transparency and traceability in all energy trading activities.

The platform's architecture follows a structured methodology based on Hyperledger Composer. It begins with an authentication process, where the administrator manages the secure onboarding of prosumers into the blockchain network. Consumers initiate energy trading by creating Energy Issue Requests (EIR), specifying details such as energy quantity, duration and the chosen producer. Producers in turn, respond to these requests, either accepting or rejecting them. Accepted requests lead to the execution of energy trading transactions, which are recorded on the blockchain ledger for transparency.

One of the key features of the platform is its user-friendly interface. A graphical user interface (GUI) simplifies interactions, allowing participants to create and monitor EIRs and access transaction histories. The platform ensures security and trust through the immutable nature of blockchain data, preventing tampering or unauthorized modifications. Its scalability also allows for the addition of new participants, making it adaptable for larger energy grids and expanding markets.

The findings from the study highlight the benefits of the blockchain-based platform. By enabling direct P2P energy trading, the platform reduces dependence on centralized authorities, thereby democratizing energy markets. The blockchain's real-time transaction updates enhance transparency, fostering trust among participants. Additionally, the flexibility of the system allows consumers to interact with multiple producers, optimizing energy procurement.

Looking ahead, the study suggests future enhancements to the platform, including the integration of smart contracts for automated energy bidding and allocation. A virtual switch mechanism could further improve the flexibility of energy transfers, while enabling consumers to request energy from multiple producers would enhance efficiency and scalability. These advancements would make the system more robust and versatile, catering to a wider range of energy trading scenarios.

The blockchain-based energy trading platform demonstrates a scalable, secure and transparent solution for decentralized energy markets. It serves as a viable alternative to traditional energy trading methods, leveraging the unique capabilities of blockchain technology. By addressing key challenges and introducing innovative features, the platform paves the way for future developments in energy management, contributing to the evolution of decentralized energy systems.

Conclusion

The transition towards a more decentralized and sustainable energy system has given rise to P2P energy trading as a promising concept. This review paper has explored the critical components that shape the design and implementation of P2P energy trading systems, including bidding strategies and energy trading models. Bidding strategies, such as truthful bidding, strategic bidding, double-sided auction bidding, and automated bidding play a crucial role in determining how participants interact with the market and make decisions regarding buying or selling energy. Each strategy offers unique advantages and challenges, influencing market efficiency, fairness and individual payoffs. Energy trading models define the platforms and mechanisms through which energy transactions occur among participants. Models such as bilateral trading, community-based trading, blockchain-based trading, centralized trading platforms, and virtual power plants have been proposed and analyzed, each offering distinct benefits and drawbacks depending on the scale of the energy system, regulatory environment and desired level of decentralization. As P2P energy trading continues to evolve, ongoing research efforts are focused on developing efficient and robust trading models, addressing challenges related to market design, cybersecurity, and regulatory frameworks. Additionally, the integration of emerging technologies, such as blockchain, artificial intelligence, and the Internet of Things, holds promise for enhancing the functionality and intelligence of P2P energy trading systems. Ultimately, the successful adoption of P2P energy trading hinges on striking the right balance between various objectives such as market efficiency, fairness, consumer empowerment and grid resilience. By fostering a collaborative and interdisciplinary approach, researchers, policymakers and industry stakeholders can work towards realizing the full potential of this innovative paradigm in driving a more sustainable and decentralized energy future.

Conflict of Interest

Authors declare no conflict of interest is there for publication of this work.

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