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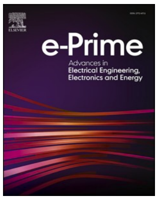

Review of peer-to-peer energy trading: Advances and challenges

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ABSTRACT

The power system is confronting progress due to the high integration of distributed energy resources (DERs). These DERs are expected to cause challenges for power system operations. Therefore, innovative management approaches were proposed for integrating DERs in future power systems and maximizing DER owners' benefits, such as peer-to-peer (P2P) energy trading. Direct energy trading between users is made possible by P2P energy trading, which supports bulk power infrastructure operations while supporting local power and energy balance. P2P energy trading is a promising approach to expanding the installation of renewable energy sources and achieving the system flexibility required for the shift to low-carbon energy. The grid is anticipated to gain from P2P energy trading by having lower reserve requirements, peak demand, and network losses. Many studies and pilot projects have shown how P2P energy trading benefits prosumers as well as the grid. However, the widespread use of such trading models remains limited in today's electrical markets. This paper reviews recent advances in the P2P energy system and a perceptive discussion of the challenges that are keeping P2P from becoming a viable energy management solution in the present electrical market. First, the energy network is covered in this paper's description of these new P2P markets; next, the types of P2P energy trading, moving on to the market structure. Then, the technologies and technical approaches behind P2P energy trading are covered. After that, P2P energy trading advances in different systems are discussed. Finally, we identify challenges before making some concluding remarks.

1. Introduction

Cleaner energy solutions are becoming the focus of attention worldwide due to climate change and environmental concerns. Energy networks, however, are witnessing a dramatic shift from conventional centralized systems to distributed systems; consumers who were previously passive are now prosumers, with their own energy sources and energy storage systems that allow them to actively control their energy production and consumption. The reduction in costs of energy storage and renewable generation has helped to expand the use of distributed energy resources (DERs) [1].

DERs are vital in enabling the integration of clean energy sources into the electrical grid, providing electricity consumers with economical and efficient energy resources, enabling grid-dependent consumers to become active prosumers, and resolving issues related to the distribution network, such as voltage fluctuations and network capacity [2]. The rapid proliferation of DERs has paved the way for a new type of trading in distribution networks called peer-to-peer (P2P) energy trading.

P2P is a next-generation energy trading technique based on the sharing economy concept [3]. It incorporates direct trading between prosumers and consumers, either with or without a central coordinator. It differs from traditional energy trading, which is unidirectional; this type of trading is bidirectional, allowing both cash and energy flow in both directions. P2P energy trading, on the other hand, promotes multidirectional trade within a local geographic area. Thus, a more decentralized and open electrical network is made possible by the enormous rise in energy prosumers [4].

P2P energy trading aims to increase economic performance, stabilize grid power when integrating intermittent renewable energy supply, and meet stochastic energy demands with a high penetration of renewable energy [5]. P2P energy trading offers a number of benefits, such as increased system efficiency [6], decreased primary energy consumption

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and required energy storage capacity [7], increased penetration of renewable energy sources with less energy lost during storage and transmission [8], avoided devaluation of energy quality, and lessened grid pressure for energy interactions. With the use of renewable energy and storage technologies, P2P-based electricity markets can help decarbonize society [9], facilitate reliable trading with PV prediction error and uncertainty [10], eliminate losses, and support local power grid congestion and voltage [11].

The community will be affected by the deployment of P2P energy trading. There will be an effect on cultural practices and lifestyles regarding the demand and supply of electricity. P2P system administration and maintenance [12] will simultaneously create local job opportunities and training programs. There will be an increase in social trust, which will improve transaction transparency and lower the number of fraudulent transactions. Moreover, a connection to the community will be developed because there will be more direct connections between participants. In light of these benefits, many projects around the world have concentrated on P2P energy trading [13].

Several recent review articles analyze P2P energy trading [14] review market designs for local energy trading with an emphasis on grid constraints, overheads, and scalability [15] investigate P2P electricity trading techniques, providing a review of their key features and the benefits they give to prosumers and the grid, focusing on market clearing mechanisms [16] review consumer-centric electricity markets that incorporate the behaviors of prosumers as well as other market participants [17] classify and organize the market designs and clearing methods, giving particular attention to local flexibility markets [18] review P2P market designs, trading platforms, physical and ICT infrastructure, social science perspectives, and policy implications [19] analyze trading platforms, blockchain, simulations, game theory, algorithms, and optimization methods used in P2P trading markets [20] concentrate on P2P market optimization models, including a comprehensive taxonomy [21] review local electricity markets, paying particular attention to the four main characteristics of the market: scope, modeling assumptions, objectives, and mechanisms [22] review bidding strategies and market-clearing mechanisms in the energy market's business layer with regard to business model dimensions. [13] review energy trading projects around the world [23] investigate the technologies that facilitate energy trading, their applications, benefits to the local communities, and analyze how blockchain and IoT technologies can help energy trading at the customer level [24] review trading pricing models, decision-making in dynamic trading behavior, and agent-based synergistic collaboration [4] review frameworks, implementation methodologies, and demonstration projects [25] review advances in the application of multi-agent systems in P2P energy trading [26] review characteristics of P2P energy trading, transactive energy, and community self-consumption [27] review market architectures, trading strategies, and enabling technologies [28] review trading environment, optimization methodology, and relevant resources [29] analyze how distribution networks operate with characteristics including reconfigured networks, mobile energy storage devices, energy markets, and the new role of participants [1] describe the differences in business models for their presence in the local energy market models, focusing on the identified customers and partner relationships, the key actors per market model, and the character of the interactions between market participants.

It can be seen that there are a lot of review papers discussing the progress in P2P energy trading done by academic studies, pilot projects, and startups. In view of the large interest in literature and industry in this research area, we have attempted to provide a comprehensive review of the technological and technical approaches that have been developed in the literature, current advances in P2P energy trading, and a perceptive discussion of the remaining challenges imposed by P2P transactions at the distribution level through the following contributions:

1. Review on P2P energy networks, P2P energy trading types, and P2P energy trading markets.
2. Discuss the technologies and technical approaches that have been used to develop various P2P energy trading systems.
3. Discuss the advances in the P2P energy system and a perceptive discussion of the remaining challenges that must be resolved in order to implement P2P energy trading.

The paper is organized in the following way: Section 2 gives background on the P2P energy network, while the types of P2P energy trading are presented in Section 3. Section 4 discusses the different market structures of P2P energy trading. Technologies commonly encountered in the current literature to implement P2P trading mechanisms are reviewed in Section 5. Section 6 gives an overview of the technical approaches used in P2P energy trading implementations. P2P energy trading advances in different systems are introduced in Section 7. Section 8 discusses challenges that need to be addressed to implement P2P energy trading. Finally, the paper concludes. Fig. 1 depicts the main topics of P2P energy trading that this paper covers.

2. Energy network

A P2P energy network is one in which participants exchange information and resources, like renewable energy and storage devices, to achieve specific energy-related goals [30]. Such goals include maximizing the use of renewable energy, reducing electricity costs, decreasing peak load, and lowering the costs of investments and network operations. Each participant can interact with other peers on the network directly and can use the network's resources as a supplier, a receiver, or both without the support of a third-party controller. Moreover, it is possible to modify the network's operational structure without adding a new peer or removing an existing one. There are two layers in a P2P network [15] the virtual layer and the physical layer.

The virtual layer provides participants with a secure connection, which allows them to select the energy trading settings. On the virtual platform where sell and purchase orders are made, all types of information are transferred, and the sell and purchase orders are matched using a suitable market mechanism. After the orders are successfully matched, financial transactions are completed.

The physical layer enables transferring electricity between sellers and purchasers after the parties have completed their financial settlements through the virtual layer platform. These virtual platform financial settlements do not guarantee the actual supply of electricity between different prosumers, and the payment might serve as a signal from purchasers to the prosumers on the P2P network to manage the distribution system's integration of renewable energy. A P2P network should incorporate a variety of components to facilitate energy trading between several prosumers.

2.1. Virtual layer elements

The virtual layer elements are information systems, market operations, pricing mechanisms, and energy management systems.

Information systems enable prosumers to trade energy by incorporating them into an appropriate market platform, having equal access to all participants, monitoring market operations, and limiting participant decisions for network reliability and security.

Market operation enables prosumers to trade energy efficiently by continuously matching trade orders. There could be variations in the market's time horizons where they should have the option to deliver a sufficient portion of energy at each step.

Pricing mechanism balances energy between demand and supply and is utilized as part of market operations. It reflects the current energy state in the P2P network; thus, it should lead to a decrease in energy prices when the network's energy excess is higher and vice versa.

Energy management system assures that the energy supply of the

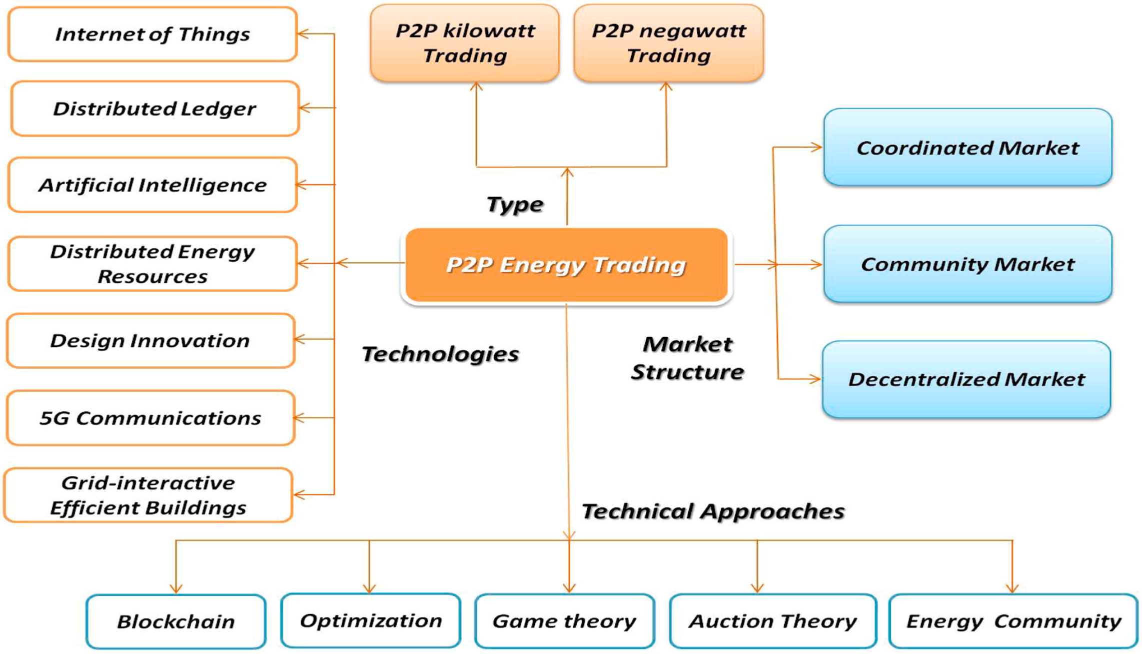


Fig. 1. A review of P2P energy trading types, market structure, technologies, and technical approaches.

prosumer is secure and is responsible for bidding and participating in trading on the prosumer's behalf.

2.2. Physical layer elements

The physical layer elements are grid connection, smart metering, and communication infrastructure.

Grid connection balances energy generation and consumption. Smart meters can be connected at these connection points to assess the P2P network's performance.

Smart metering uses information about supply, demand, and market conditions to decide whether or not each prosumer engages in the P2P market.

Communication infrastructure discovers prosumers and facilitates the exchange of information with the network. Security, throughput, latency, and reliability performance requirements must be met by the communication infrastructure chosen.

2.3. Other elements

Prosumers are necessary for implementing energy trading in a P2P network. P2P energy trading must have a sufficient number of prosumers to be successful. It is essential to specify P2P trading's goal since it has an impact on how pricing structures are created and how the market operates.

Regulators and energy policy determine whether P2P energy trading is successful. The types of market designs that are permissible, the distribution of taxes and fees, and the incorporation of the P2P market in

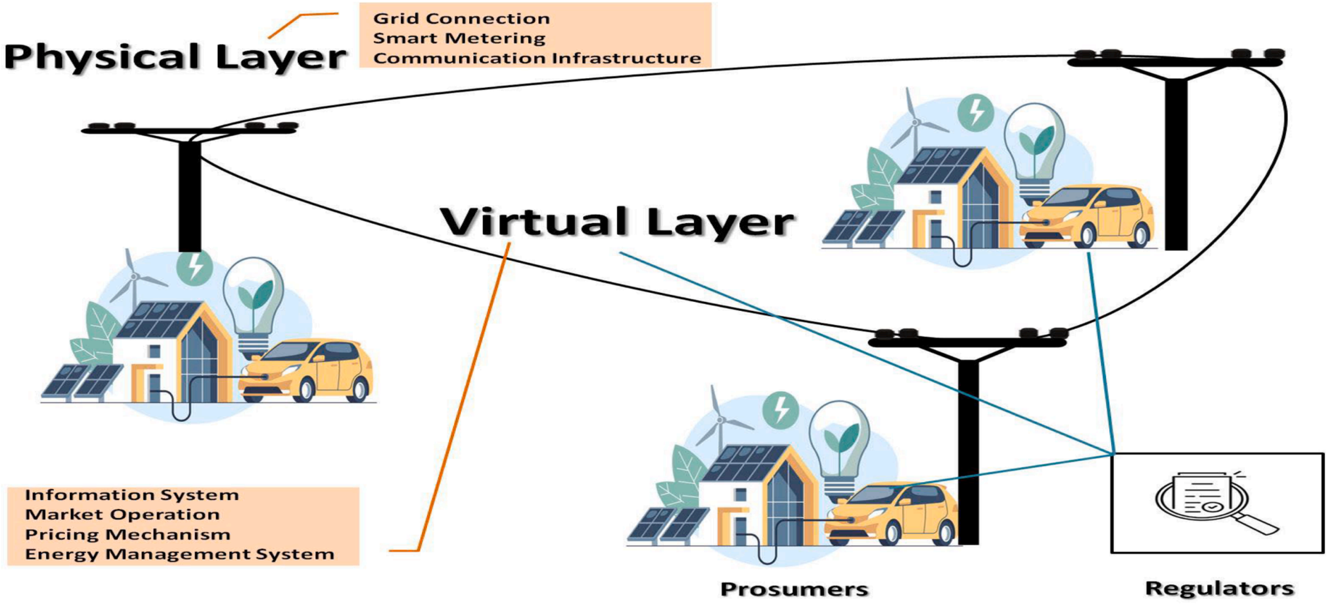


Fig. 2. P2P energy network elements.

energy supply and market are all determined by the regulations that apply in a particular country. In order to minimize environmental degradation and accelerate the efficient use of renewable energy resources, governments should promote P2P markets. P2P network elements are depicted in Fig. 2 [31].

3. Trading types

Based on prosumers' dispatching flexibility, P2P energy trading may be classified into two types [32]: P2P kilowatt (kW) trading and P2P negawatt (nW) trading.

In P2P kW trading, prosumers with excess energy make financial transactions with prosumers who are interested in purchasing energy [15]. On the other hand, P2P nW trading directs prosumers to sell their right to purchase energy by lowering their internal demand in accordance with agreements made with other prosumers [33].

P2P kilowatt (kW) trading: Under this trading mechanism, sellers trade excess energy with purchasers on a virtual platform. Prosumers are permitted to decide amounts to trade with one another at agreed-upon pricing. A consumer can participate in trading as a purchaser if they have no local generation. Once trading and price amounts are virtually settled, sellers inject the negotiated kW amounts into the distribution network. [34] proposes a novel P2P kW trading strategy to achieve optimal energy transactions in high-penetration distribution systems, demonstrating its ability to reduce internal energy imbalances and improve economic benefits for prosumers. A new dynamic operating envelope-integrated P2P kW trading system to increase the exchange of electricity from prosumers to a distribution network is proposed in [35], which increases the exchange of electricity from prosumers to a distribution network. Consequently, prosumers can significantly reduce their electricity costs by engaging in more locally traded power. The analysis conducted in [36] shows that more than half of the prosumers surveyed are familiar with the P2P kW trading market and would like to engage in transactions related to the trading of household-generated electricity.

P2P negawatt (nW) trading: Under this trading mechanism, prosumers control how much energy they consume in order to support distribution networks' energy balance. This control is based on virtual, bilateral contracts. It allows prosumers to trade with one another in the market through P2P platforms. When nW amounts and prices are matched on a virtual platform, P2P nW sellers lower their planned demand, and P2P nW purchasers are able to use the excess demand from the connected network. The application of P2P negawatt trading at the distribution level is emphasized to reduce the electricity costs of the prosumers in [37]. The low-voltage distribution network's voltage-constrained P2P nW trading mechanism is formulated in [38], and financial analysis is done to demonstrate the system's viability as a substitute for demand-side management. A token-based hybrid market model for P2P nW trading is implemented in [39] as a decentralized application running on the Ethereum public blockchain.

Some articles joint P2P kW trading and P2P nW trading together. For instance, [40] presents a novel unified P2P framework for both kW and nW trading to coordinate these two transaction types to maximize customer benefits by lowering electricity bills and facilitating energy trading between customers and neighbors while respecting the physical limits of electricity networks. In an effort to meet the energy demand and improve the financial benefits for participants, a combined kilowatt and negawatt trading system is being tried in a local market with solar electricity generation in [41].

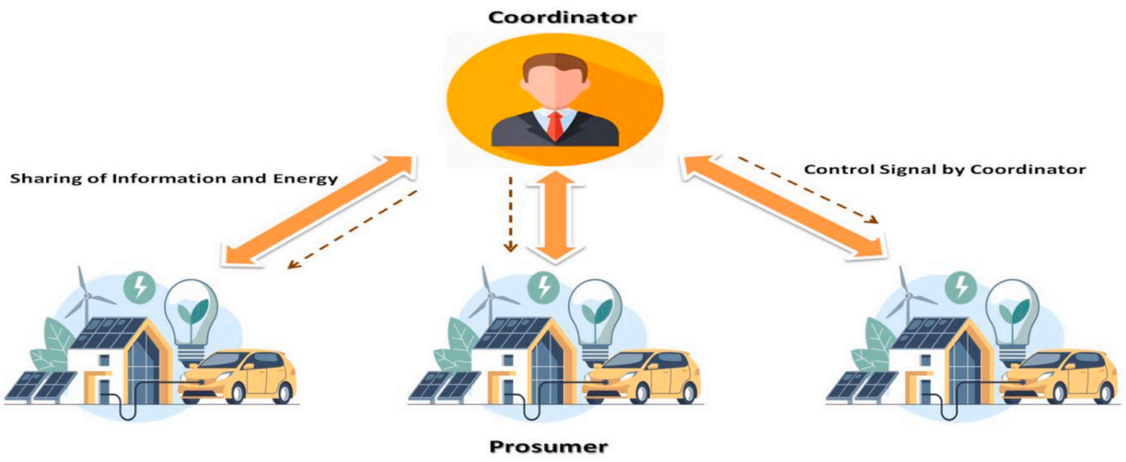
4. Energy markets

The structure of the P2P energy trading market is separated into three types based on the sharing of information and trading mechanism between network participants: coordinated, community, and decentralized markets [31]. P2P energy market structures are depicted in Fig. 3.

Coordinated market: Sharing information and trading mechanism are centralized in this market. A centralized coordinator interacts with each prosumer in the network and controls the energy imports and exports that the prosumers trade between them. Prosumers do not share information or negotiate energy trading parameters with one another; however, they might influence the decision-making process by separately determining their energy and price before informing the coordinator. This market may compromise the privacy of prosumers. A novel P2P coordinated market design is proposed in [42] for the distribution grid level. It is demonstrated that the proposed P2P trade can effectively support grid operating objectives. A coordinated P2P trading model with an aggregated alliance and reserve purchasing is proposed in [43]. The proposed market model can effectively assure convergence, lower the deviation penalty, and enhance overall welfare. A hierarchical approach for local energy and flexibility trading between prosumers in distribution networks is proposed in [44]. The proposed method enables prosumers to manage their resources and participate in a P2P market. The P2P energy trading market between prosumers is managed by a local market operator who operates in coordination with the distribution system operator to distribute the flexibility that prosumers provide. Further example of P2P trading within the coordinated market can be viewed in [45].

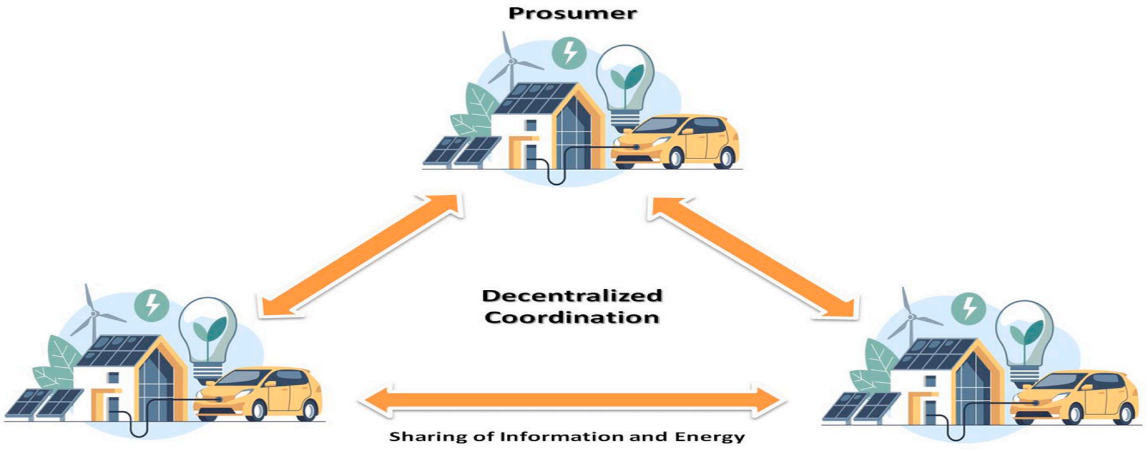
Community market: Sharing information is centralized, while trading mechanism is decentralized in this market. Prosumers trade energy through a community manager, who serves as a trade coordinator and has no control over the energy imports and exports by various prosumers in the market. Prosumers are indirectly encouraged to participate by the community manager through the use of suitable pricing signals. Thus, prosumers can preserve their privacy by providing the community manager with limited information [46]. An appropriate community market design is proposed in [47], which solves the problem of resource allocation and maximizes social welfare. The manager-based energy market facilitates energy trading within the community and, if needed, with other communities. However, it requires collecting data from all market participants and solving a centralized optimization problem. [48] proposes a trading model for a community-based P2P electric energy market that involves prosumers, pure energy consumers, and local energy suppliers as well as a community coordinator. Results show great effect on reducing the net peak load and increasing the market participants' profit. [49] conducts agent-based simulations to study the benefits of the community energy market to consumers and prosumers. The proposed market results in cost savings for consumers and profit for prosumers, while increasing the energy suppliers' financial benefits. For more examples of P2P trading in the community market, see [50–54].

Decentralized market: Sharing information and trading mechanism are decentralized in this market. Prosumers decide their trading parameters directly with one another, with no centralized coordinator. Prosumers have complete influence over the decisions they make. Their privacy is protected, and they have complete control over whether or not they participate in trading. However, the efficiency of decentralized markets is generally inadequate, and social welfare does not reach its optimum value due to a lack of centralized control. It is more difficult for service providers to manage the decentralized market because of the difficulty in maintaining network constraints and increasing the power system's operational efficiency when the total amount of energy that can be traded within the community is not obvious to third parties [55]. A fully decentralized market mechanism is designed in [56], which considers prosumers preferences, including their desire to trade green energy. Prosumers with surplus or deficiency of power are incentivized to participate in the market on an individual basis while preserving their privacy [57] proposes a decentralized P2P energy trading market that facilitates electrical energy trading between customers. The proposed P2P market allowed the prosumers to freely trade energy in this market infrastructure without any third-party supervision. [58] provides a fully decentralized approach for a local P2P energy trading market. Results



(a) Coordinated Market

(b) Community Market



(c) Decentralized Market

Fig. 3. P2P energy market structure.

show how P2P markets can help customers manage their energy in their local communities [59] presents a fully decentralized P2P energy market considering the technical constraints of the physical electricity network. Prosumers can trade energy directly with each other without the need for intermediaries [60] presents a fully decentralized framework for smart homes to participate in the P2P energy market. Through bilateral trade, smart homes exchange their excess energy with one another to keep the balance between supply and demand. See [61–64] for other examples of P2P trading in a decentralized market.

Table 1 summarizes the types of market structures for P2P energy trading.

5. Technologies

P2P energy trading has grown successfully as a result of various technological developments. These new technologies include:

Internet of Things: IoT is the network that connects the computers that are a part of our everyday lives, enabling data sharing between them to achieve energy savings, predictive maintenance, condition monitoring, remote monitoring, and control [65]. There are four layers in it: device, network, cloud management, and application. The primary functions of the device layer are to sense the surroundings, collect data, and control flexible loads inside buildings, while the network layer connects the application layer and the devices. The cloud management layer guarantees user verification and data management. By controlling flexible loads, the application layer offers end-user services (demand management, dynamic pricing, energy management, and home security services). Prosumers participate in P2P energy trading by monitoring their own energy production and consumption, managing and controlling the patterns of consumption of various appliances, and establishing rules that allow the devices to trade energy across the electrical network. IoT has greatly helped in implementing P2P energy trading as an energy management strategy in the electricity market by making all these tasks possible.

Distributed ledger technology: DLT is a digital, shared, and distributed database that records asset transactions and could improve the efficiency of current energy sector procedures. DLT is effective in tending to P2P energy trading mechanisms, data privacy, security, integrity, and speed of financial transactions among prosumers [66]. It accomplishes this by giving prosumers access to a secure platform where they may communicate information for energy and financial transactions without needing third parties, which is necessary for decentralized information communication. Ledgers, smart contracts, and consensus protocols are the main components of any distributed ledger technology [67]. Ledgers record participant information and data; smart contracts describe participant decisions to assure agreement between two or more implemented parties. Transactions are verified by consensus protocols.

Artificial intelligence: AI in general describes computing methods that imitate human intelligence in order to give machines the ability to think critically and behave sensibly [68]. AI-powered machines exhibit characteristics of the human mind, like problem-solving and learning. AI offers advances in computational methods that may change how agent-based systems are mechanized and make decisions. AI techniques are commonly applied in P2P energy trading to understand how different flexible loads utilize energy and adjust their energy methods accordingly. This helps achieve various goals, including demand-response through reinforcement learning [69], building management through deep learning [70], and reducing energy costs with artificial neural networks [71]. The development of these computational methods would be crucial for understanding prosumer decision-making.

Distributed energy resources: DERs are localized small-scale power generation units that have connections to a larger power grid at the distribution level. Uncontrolled DERs cause reverse power flows, which raise voltage and increase current faults in the electrical network, which can result in power outages [72]. To avoid this, PV inverters, battery storage, electric vehicles, and flexible loads are used for controlling DERs [73]. PV inverters are sufficiently smart to automatically modify how much active and reactive power they inject into the electrical network based on the condition of the network [74]. Prosumers can utilize the energy that is stored in their vehicles' batteries by controlling the electric vehicle's charging and discharging and using flexible load management [75].

Design innovation: DI is a trans-disciplinary, human-centered method that utilizes technology and user interfaces to better reflect customer preferences in energy management methods. P2P energy trading has been recognized as an energy management method that is both technological and socio-technical, with the design of the P2P mechanism taking participants' preferences into consideration. DI provides a collection of technologies that enable prosumer-centric management of energy production and consumption in buildings [76] so that the buildings can take part in the energy trading market using the 4D model (discover, define, create, and deliver).

5G ***communications:*** A high-speed communication infrastructure with low latency that can facilitate immersive distant operations and interactions with the actual environment is required for the success of P2P energy trading in the energy market [77]. The fifth-generation (5G) communication networks necessary to satisfy this requirement have the ability to support highly demanding applications and services and push the network capacities to give significant performance benefits [78]. This involves having the capacity to support a high number of networked devices and providing the services required to reliably facilitate operations and control of physical objects over long distances with low response latency. P2P energy trading will be made possible by a number of interconnected devices that the 5G network will make available.

Grid-interactive efficient buildings: GEBs refer to buildings that are able to modify their energy production, consumption, and sharing in line with incentive signals that other buildings, third parties, or the grid send [79]. GEBs are able to manage and regulate their energy production in real time, in addition to optimizing energy use based on customer demands and preferences and providing energy-related services to the network. GEBs have a reliable and secure system that is not vulnerable to

Table 1
Types of P2P trading markets.

Type of Market	Trading Mechanism	Sharing Information	Merits	Challenges
Coordinated market [42-45]	Centralized	Centralized	- Coordinator has direct control over the operational state of prosumers. - Maximizes social welfare.	- Compromise the privacy of prosumers. - Extensive computational burden.
Community market [46-54]	Decentralized	Centralized	- Prosumers can preserve their privacy while sharing limited information with the community manager. - Enhances prosumers' social cooperation and flexibility.	- Simulating Prosumers' decision-making processes and putting the planned pricing signals into action. - Fairness and impartiality for energy trading between prosumers.
Decentralized market [55-64]	Decentralized	Decentralized	- Prosumers have complete influence over the decisions they make, and their privacy is protected. - Prosumer-centric properties.	- Energy trading is not obvious to third parties. - Efficiency is relatively low, and social welfare does not attain its maximum value.

outside cyber-attacks; reliable and low-latency bilateral communication and connectivity with devices and appliances inside the buildings and with other GEBs in the network; together with an intelligent management system that can predict, monitor, and take into account occupant demands and preferences; weather forecasts; and market conditions; and subsequently, reduce their energy consumption [80].

6. Technical approaches

Five general techniques can be considered the main contributions to the design of current P2P energy trading networks based on the approaches used in current studies: blockchain, optimization, game theory, auction theory, and energy community. A summary of the technical approaches applied to P2P energy trading is shown in Fig. 4 and Table 2.

6.1. Blockchain

Blockchain technology is intended to decentralize transactions and enhance security. Blockchain is a distributed database that can securely store important data, events, contracts, and financial transactions. Important data is stored in blocks and connected by chains. Blockchain technology is applied to the energy sector in a number of ways [81]: business models, research articles, and pilot projects. The following is a summary of the P2P energy trading that is enabled by blockchain-based platforms:

- ***Smart contracts:*** A blockchain-based programs that automatically and deterministically execute agreements based on predefined conditions. A blockchain-based smart contract model is introduced in [82] for distribution and P2P transactions in the energy market. Using smart contracts expedites the trade of electricity and lowers transaction costs. In a smart grid, a P2P energy token market that is fully decentralized is designed [83] for small-scale prosumers utilizing blockchain-based smart contracts. Smart contracts enable P2P transactions between sellers and purchasers at a set price, with the retailer and each other at an agreed-upon price. Large producers and consumers in transmission systems were not taken into consideration in this paper. Also, a variety of demand response programs in the prosumers model were not used, such as peak shaving and frequency control.
- ***Elecbay:*** A blockchain-based software platform that allows peers to perform distributed transactions. A P2P energy trading platform called Elecbay was developed in [84]. Results indicate that P2P energy trading can assist in achieving a balance between locally produced and consumed energy. The possibility of changing prosumers' and consumers' energy-consuming behaviors was not covered in this study. Conflicts between social dissatisfaction and economic performance will arise as a result of these changes. In [85], the bidding system Elecbay for P2P energy trading in a microgrid connected to the grid is proposed. P2P energy trading is shown to be capable of balancing local supply and demand. This study did not investigate different control methods by using the load profiles of prosumers obtained in the P2P energy trading.
- ***Ethereum:*** An open-sourced blockchain that is designed to efficiently implement P2P information sharing. It is based on the concept of the native cryptocurrency Ether. In [86], an Ethereum blockchain-based P2P energy trading platform and smart contract are developed to control financial transactions and energy exchange operations for energy trading systems by the integration of decentralized application technology. An Ethereum-based P2P energy trading system is proposed in [87] to facilitate secure and economical energy trading. The design and implementation of energy trading in several energy agents, multiple distribution networks, and dispute resolution procedures for when the trading process encounters difficulties were not covered in this study. An Ethereum blockchain-based energy trading solution and smart contracts are suggested in [88] to satisfy energy demand, lower transaction costs and settlement times, ensure transaction security, and make the energy market dynamic and decentralized.
- ***Hyperledger:*** An open-source blockchain is one of the Linux Foundation's efforts. Its objective is to offer a stable framework for Sawtooth, Indy, Hyperledger Fabric, Hyperledger Caliper, and Hyperledger Ursa. A blockchain-based energy trading system is proposed in [89] using Hyperledger Fabric to prevent the exposure of consumption patterns by enabling certified renewable energy exchange with purchasers. This study did not explore the full extent of

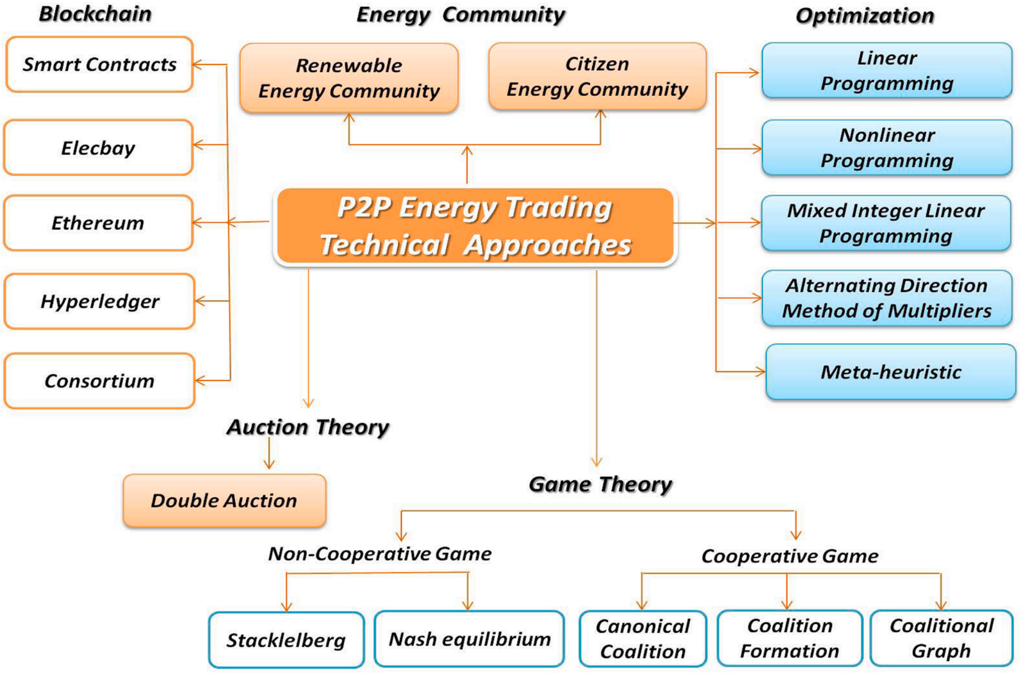


Fig. 4. Technical approaches applied in P2P energy trading.

Table 2
Summary of the technical approaches used to facilitate P2P energy trading.

Technical Approach	Method	Main Objective of the Method	Refs.
Blockchain [81,94-100]	Smart contracts	A blockchain-based program that automatically and deterministically executes agreements based on predefined conditions.	[82,83]
	Elecbay	A blockchain-based software platform that allows peers to perform distributed transactions.	[84,85]
	Ethereum	An open-sourced blockchain that is designed to efficiently implement P2P information sharing. It is based on the concept of the native cryptocurrency Ether.	[86–88]
	Hyperledger	An open-source blockchain is one of the Linux Foundation's efforts. Its objective is to offer a stable framework for Sawtooth, Indy, Hyperledger Fabric, Hyperledger Caliper, and Hyperledger Ursa.	[89–91]
	Consortium	A blockchain that creates a cost-effective distributed shared ledger utilizing approved nodes.	[92,93]
Optimization	Linear programming	A mathematical programming technique that optimizes linear objective functions with linear constraints.	[101–103]
	Mixed integer linear programming	A specific instance of the integer LP technique, with some variables being integers and others being non-integers.	[104–106]
	Nonlinear programming	A mathematical technique used to solve optimization problems, including nonlinear objective functions and nonlinear constraints.	[107,108]
	Alternating direction method of multipliers	An algorithm that divides convex optimization problems into simpler parts so that each may be solved accurately and conveniently.	[109,110]
	Meta-heuristic optimization algorithms	Mathematically-based tools for solving complex optimization problems, usually nature inspired.	[111,112]
Game Theory	Stacklelberg game	A strategy game in which one or more players are considered leaders because they commit to a strategy and make decisions before the other players.	[113,114]
	Nash equilibrium	A stable state in a non-cooperative game where, when every other player is following their own Nash equilibrium strategy, no player can benefit more from unilaterally acting differently.	[115,116]
	Canonical coalition game	The primary goals are to ascertain whether or not a grand coalition can be established, and to create a reasonable revenue distribution plan to share the coalition's benefits among its members.	[117]
	Coalition formation game	The primary goal is to investigate how a coalitional structure forms as a result of player interactions, as well as the characteristics of the structure and how well it adjusts to changes in the surrounding environment.	[118]
	Coalitional graph game	Focus on how players may communicate with each other. The primary goals are to explore the features of the graphs and to design low-complexity distributed methods for players who wish to construct network graphs.	[119]
Auction Theory	Double auction	An approach to distributing financial resources that balances supply and demand through a competitive bidding technique	[120–125]
Energy Community [126–131]	Renewable Energy community	Based on open and voluntary participation, it is autonomous and is efficiently controlled by shareholders or members that are near renewable energy projects that are owned and operated by legal entities. The primary purpose is to provide benefits for its shareholders or members or for the local areas where it operates, rather than financial profits.	[132–134]
	Citizen Energy community	Based on voluntary and open participation, it is efficiently controlled by members or shareholders that are natural persons, local authorities such as municipalities, or small enterprises. The primary purpose is to provide benefits to its members or shareholders or to the local areas where it operates rather than to generate financial profits.	[135–139]

the change of multiple configuration parameters by Hyperledger Fabric. A benchmark based on the Hyperledger Caliper tool is provided in [90] to assist application designers and developers in selecting the optimal implementation model between the two most recent stable versions of the Hyperledger Fabric model. This study did not examine the performance of other commercial clouds. Also, they did not employ real-time energy demand and price before configuring chain codes. The recommended architecture for recording energy transactions includes a Java script-based smart contract over the Hyperledger Sawtooth proof of elapsed time, as proposed in [91].

- ***Consortium:*** A blockchain that creates a cost-effective distributed shared ledger utilizing approved nodes. A consortium blockchain based on a distributed energy trading system is suggested in [92]. Results show that the system has excellent security in distributed energy transaction situations and can complete a transaction matching the optimal price and quantity in time-of-use electricity price. The distributed energy network includes a variety of energy sources, including natural gas and heating networks, but how to fully utilize them is not covered in this study; instead, only electric energy is examined. For vehicle-to-grid demand response management, a consortium blockchain-based system is created in [93] to ensure secure energy transactions.

Many studies developing blockchain-based platforms are introduced, which is positive from the perspective of technical development. However, little information is provided regarding the challenges for practical implementation and drawbacks of using blockchain, like regulation, legal barriers, low transaction processing rates, and high transaction fees. Many of these challenges represent a barrier to blockchain implementation in P2P energy trading. Regulation is a significant barrier to blockchain implementation [94]. For instance, while regulations in certain nations permit consumers to actively participate through the installation of local generation or storage, they do not permit significant modifications to P2P energy trading or the integration of DLTs within the current systems, which prevents the large-scale implementations of similar applications regardless of the level of technological readiness [95]. Therefore, new energy market regulations are required in order to enable local energy markets and energy exchange at a local level, as well as allowing DERs to participate in grid-wide energy and ancillary services markets. Because utilities often wait for regulations and technological advancements to take hold before making investments, these constraints will delay their implementation of blockchain technology. Moreover, most studies and pilot projects investigating blockchain applications in the energy sector focus on unregulated energy markets. As a result, blockchain applications in the energy sector should receive more attention. Considering regulated or partially unregulated energy markets, their added value should be assessed, as higher constraints to the implementation of new technologies are anticipated in these markets than in unregulated ones [95].

Blockchain technology gives network participants an unchangeable copy of their data, which, in the event of a public blockchain, may be accessible to all individuals. This characteristic raises concerns regarding numerous data privacy regulations [96,97]. For instance, the General Data Protection Regulation (GDPR) sets regulations that apply to blockchain technology applications in the energy sector [98]. According to the regulations, sensitive data must be managed by a legal person, be maintained in a minimum number of copies, and be able to be modified or removed. These regulations may have an impact on how blockchain technology is used in the energy sector, given that the blockchain will be used to store sensitive data relating to different stakeholders.

Widespread use of blockchain technology in the smart grid necessitates pricey ICT infrastructure upgrades appropriate for blockchain operations as well as modifications to smart meters. For instance, the Quartierstrom project, a community-based local energy market, necessitated the use of a smart meter with an application processor, a feature not available in existing smart meters [99]. Furthermore, it is necessary to install smart meters with a suitable time resolution; this will require higher costs and time to implement throughout the country. Blockchain-based local energy markets require communication technologies with a data rate of >1000 kbit/s, according to the Quartierstrom project's results. As a result, some communication technologies are not appropriate for this application because of their low data rates [100]. This cost might discourage or delay the widespread adoption of P2P energy trading or blockchain technology by utilities. Moreover, the high cost of performing computations on the blockchain and the absence of certain mathematical functions limit the computations that can be done on the blockchain.

6.2. *Optimization*

Optimization is a technique for maximizing profits or minimizing losses. P2P energy trading optimization techniques are designed to minimize prosumer energy losses, maximize user economic benefits, and balance microgrid energy supply and demand. P2P energy trading can be formulated as an optimization model, and market clearing can be achieved by solving the optimization problem. The P2P energy trading that is made possible by optimization techniques is summarized as follows:

- ***Linear programming:*** LP is a mathematical programming technique that optimizes linear objective functions with linear constraints. A P2P energy trading market is constructed in [101,102] as a linear multi-period optimization problem to assess how prosumer trading affects the phase unbalance of a LV distribution network. These studies did not consider the uncertainties associated with demand profiles, PV generation, electricity prices, and EV arrival time. These also did not study the impacts of P2P energy trading on different distribution networks due to the diverse characteristics of distribution networks. Ref. [101] uses different electricity tariffs (flat tariff and time of use tariff). In [103], a completely data-driven, robustly distributed optimization for P2P energy trading is proposed in a decentralized energy market. P2P energy trading price is formulated with feed-in price. The equivalent LP reformulations of the suggested model are executed and resolved in a distributed manner. The network constraints in P2P energy trading were not taken into consideration in this study.
- ***Mixed integer linear programming:*** MILP is a specific instance of the integer LP technique, with some variables being integers and others being non-integers. An optimization model that considers integrated demand-side management is created in [104] to assess P2P multi-energy trading between both commercial and residential prosumers. A major increase in computational performance is achieved when the complex problem is linearized as a MILP model. The time-of-use pricing is used to formulate the P2P energy trading price. As more prosumers enter the P2P energy trading framework, more work is needed to solve the model effectively. A P2P energy trading system for buildings that considers multi-energy connections is provided in [105] in an attempt to reduce costs and increase energy efficiency by formulating a MILP to maximize total profit. All peers aim to maximize their revenue and create trading strategies based on the time-of-use tariff released by the main grid. Uncertainties such as PV output and forced outages of micro-combined heat and power and electric heat pumps are not considered. Transactive networked multi-carrier energy systems are given a two-stage fairness model in [106] with a MILP structure. The suggested two-stage optimization strategy satisfied the fairness issue and reduced the networked multi-carrier energy systems' operating costs by 16.7 %. The impacts of fairness on human-based decisions were not examined.
- ***Nonlinear programming:*** NLP is a mathematical technique used to solve optimization problems, including nonlinear objective functions and nonlinear constraints. In [107], a stochastic Cartel NLP model is developed to minimize the overall cost of several microgrids while characterizing joint energy bidding, energy generation, and P2P energy transactions. It is difficult to use the proposed strategy to address energy bidding from ultra-larger-scale microgrids, as there are only limited microgrids in regional distribution networks. Also, the proposed strategy only provides useful insights to analyze potential bid actions for multiple microgrids; thus, network constraints were not considered in the energy bid process. A two-stage aggregated control is suggested in [108] to realize P2P sharing in community microgrids. The community's energy costs were minimized by using constrained NLP optimization.
- ***Alternating direction method of multipliers:*** ADMM is an algorithm that divides convex optimization problems into simpler parts so that each may be solved accurately and conveniently. As suggested in [109], the optimization problem in an industrial town was simulated and solved using the ADMM algorithm. Impact of P2P and battery energy storage system energy exchange in a centralized and

decentralized approach is analyzed. It was not taken into consideration how distribution network constraints impacted peer transactions. A P2P energy trading system between several virtual power plants is proposed in [110]. The benefits of virtual power plants and renewable energies are enhanced overall using ADMM. Uncertainty of renewable energy forecasting is not considered.

- ***Meta-heuristic optimization algorithms:*** MHOA are mathematically-based tools for solving complex optimization problems. A bi-level optimization problem resulting from energy trading is solved by evolutionary algorithms (EAs) in [111]. EAs are able to offer all agents a way to improve their profits. Transactions in local energy markets did not consider the effect in the distribution network and network constraints before implementation. Ant colony optimization (ACO) is used in [112] for learning bidding strategies within a bi-level optimization framework that emerges from energy trading in local energy markets. ACO can help agents learn strategically and provide solutions that will raise profits for all agents.

6.3. Game theory

Game theory is a mathematical approach that studies player behavior in structured incentive structures known as games through models. Game theory was employed by researchers to simulate P2P participants' behavior. Game theory can be classified into two categories: non-cooperative games and cooperative games.

- ***Non-cooperative game:*** The process of making strategic decisions by several independent actors with partially or totally competing interests is investigated to determine the consequences of their decisions. In these types of games, participants make decisions independently of one another. Non-cooperative games can be classified into:

  1. Stacklelberg game: A strategy game in which one or more players are considered leaders because they commit to a strategy and make decisions before the other players. The followers in the game are other players who adjust their strategy in reaction to the leader's actions. Stackelberg game theory is created in [113] to investigate the P2P energy trading mechanism. P2P increases the use of renewable energy sources and reduces dependency on the grid, which has positive effects on the economy, environment, and technology. A novel framework based on the Stackelberg game for multi-microgrids is suggested in [114]. It has been demonstrated that the two-stage solution method and the suggested P2P energy trading model are superior and effective. The P2P energy trading model did not take into account the impact on different power network topologies.

  2. Nash equilibrium: A stable state in a non-cooperative game where, when every other player is following their own Nash equilibrium strategy, no player can benefit more from unilaterally acting differently. To find P2P transactive energy trading, a distribution locational marginal price parameterized alternating direction method of multipliers algorithm is proposed by the prosumers in a generalized Nash equilibrium, which is investigated in [115]. This study did not consider researching the system resilience affected by P2P energy trading and the influences of prosumers' duality on the market equilibrium. In [116], a two-game interwoven P2P energy trading market equilibrium model is proposed. A generalized Nash equilibrium problem concerns how users compete with one another. The two games interact as a mixed-integer linear program, which is a holistic equilibrium problem solved by linearization techniques. It demonstrated that players profit from P2P. Uncertainty of renewable energy generation and load profile was not considered.

- ***Cooperative game (coalitional games):*** Characterized by incentives that can be used to convince decision-makers to work in cooperation to advance their position in the game. Coalition games can be classified into:

  1. Canonical coalition game: No player ever suffers a negative outcome from forming a grand coalition. The primary goals are to ascertain whether or not a grand coalition can be established and to create a reasonable revenue distribution plan to share the coalition's benefits among its members. A bilateral P2P energy trading strategy under single contract and multi-contract market configurations as canonical coalition games is proposed in [117]. The market that is being suggested makes it possible to compute market equilibrium quickly and preserve the intended economic characteristics. Uncertainty in renewable energy generation and demand was not taken into account.

  2. Coalition formation game: The primary goal is to investigate how a coalitional structure forms as a result of player interactions, as well as the characteristics of the structure and how well it adjusts to changes in the surrounding environment. A coalition formation game is suggested in [118] to assist each prosumer in making an optimal decision about whether to engage in the P2P market using their batteries. The impact of P2P trading on bus voltages and the overall losses of the network was not investigated.

  3. Coalitional graph game: Focus on how players may communicate with each other. The primary goals are to explore the features of the graphs and to design low-complexity distributed methods for players who wish to construct network graphs. In a P2P energy trading system based on coalition graph games, prosumers can form coalitions and engage in negotiations to determine energy trading parameters, including pricing and trading quantities [119]. Compared to the feed-in tariff and coalition game model without mutual negotiations, the results demonstrate that prosumers can reduce their overall electricity costs, which also allows them to export power without causing high voltage problems in the network. P2P implementation did not investigate at different distribution levels.

6.4. Auction theory

An auction is an approach to distributing financial resources that balances supply and demand through a competitive bidding technique [120]. Multiple purchase and sales orders can be concurrently submitted to the auctioneers by multiple possible purchasers and sellers in the auction market. The auctioneer then sets a clearing price for the goods. Goods are sold by sellers whose asking prices are lower than or equal to the clearing price, while goods are purchased by purchasers whose prices are higher than or equal to the clearing price [121]. The goal of an energy auction is to find the best offer that minimizes costs while balancing supply and demand for energy [122]. The auction theory is divided into three classifications: reverse auction, in which many sellers bid services/goods the purchaser requests; forward auction, in which many purchasers bid for services/goods that are being sold. Since several sellers and purchasers are typically involved in P2P energy trading, the reverse and forward auction models are inappropriate for energy trading. For modelling the P2P energy market clearing, where many purchasers price to purchase goods/services from many sellers, only double auctions have been extensively used. A P2P energy trading model based on iterative double auctions and blockchain technology in a microgrid is presented in [123] to maximize social welfare. How blockchain networks recover and continue the double auction algorithm in the event of failure of one or multiple nodes was not studied. Using a double auction-based game theoretic approach, [124] studies a P2P energy trading system between prosumers in order to increase participants' revenues and decrease grid impacts. A comparative double auction technique is employed in [125] to evaluate the relevance of four different double auction mechanisms with the goal of enhancing P2P energy trading. This study did not investigate network constraints such as voltage management and power factor.

6.5. Energy community

It can be seen from the reviewed studies the numerous benefits of P2P energy trading. However, these studies propose a very complex market designs that cannot be implemented currently. The current regulations in many countries adopt energy communities as a simple approach for energy sharing between end customers.

The energy community refers to a cooperative of consumers and/or prosumers who share energy generation units and electricity storage. Energy communities play a significant role in the energy transition of many countries worldwide through the coordination of citizen-driven energy actions. This conceptual definition has been discussed in many articles. For instance, [126] analyzed the impact of different sharing coefficients on the economic benefits of the members of an energy community [127] and developed a model to optimize local energy communities by using two different sharing strategies, like static and variable coefficients. Results indicate that a local energy community well optimized can fulfill economic, environmental, or self-consumption goals [128], achieving an adequate economic optimization focused on obtaining the distribution coefficients that maximize the net present value of the collective installation.

The European Union (EU) introduces the concept of energy community into the EU law by defining Clean Energy Package (CEP) [129]. According to the CEP, there are two types of the energy community concept: Renewable Energy Community (REC), regarding to Directive (EU) 2018/2001 (the recast renewable energy directive) [130], and Citizen Energy Community (CEC) regarding Directive (EU) 2019/944 (the recast electricity directive) [131].

- **Renewable energy community**

Renewable energy community is based on open and voluntary participation according to the applicable national law and is autonomous, which is efficiently controlled by members or shareholders that are near renewable energy projects that are owned and operated by legal entities. The members or shareholders of which are natural individuals or local authorities such as municipalities. This prioritizes social, economic, and environmental benefits over financial gains for the benefit of its members, shareholders, and the communities in which it operates.

A novel mathematical model for a REC that takes into consideration three different economic theories for the allocation of benefits among community members is proposed in [132]. RECs are supplied with an optimization model that supports their investment decisions in renewable technology and operational electricity sharing in [133]. The modeling of renewable energy communities with multiple investing members and the integration of storage technologies were not taken into consideration in this study. A comprehensive framework is presented in [134] to improve incentive alignment, privacy, and cooperation within RECs.

- **Citizen energy community**

Citizen energy community is based on open and voluntary participation, which is efficiently controlled by natural individuals, including members or shareholders, local authorities such as municipalities, or small enterprises. Has as its primary goal to benefit its members, shareholders, and the local community in which it operates, rather than to make a profit. It may also engage in the following activities: generation, including from renewable sources; distribution; supply; consumption; aggregation; energy storage; energy efficiency services; electric vehicle charging services; or other energy services for its members or shareholders.

A clean energy package-based integrated concept for citizen energy communities and renewable energy communities is proposed in [135]. An innovative physical and managerial framework for the effective management of a sub-community in citizen energy communities is introduced [136]. The concept and benefits of CEC at the distribution system level are discussed in [137]. The benefits of CECs during the negotiation of private bilateral contracts of electricity are proposed in [138]. The behavior of competitive local citizen energy communities participating in wholesale markets is studied in [139].

7. Advances in different systems

Advances in technological and technical research have contributed to the successful implementation of energy trading in P2P networks. Three systems emerge from recent research, namely: renewable energy, smart building energy, and storage energy. Fig. 5 and Table 3 depict a summary of different systems in the energy network.

7.1. Renewable energy

The rapid development of renewable energy sources has been observed across the world. Renewable energy sources, including solar, wind, and hydrogen, are gaining popularity. Trading renewable energy is the most common and extensively studied P2P energy trading system. It benefits prosumers by allowing them to have cost-effective, clean energy without needing to purchase energy storage.

7.1.1. Solar

Solar energy is the heat and radiant light from the sun that may be collected and used in a number of ways to generate electricity. It is a vital renewable energy source. The majority of P2P energy trading is designed with solar energy as the primary source of energy. Thus, using solar reduces energy costs, balances demand and supply, lowers peak demand, and controls losses in the network. Distributed PV systems are intended to use a P2P electricity trading mechanism [140]. P2P trading has the potential to significantly increase benefits and increase local self-consumption rates. In residential communities connected to the grid and equipped with distributed PV systems, P2P electricity trading is suggested in [141]. P2P offers additional motivation to increase PV self-consumption rates and can distribute profits effectively. In [142], a novel approach to energy management that incorporates demand-side management into P2P energy trading is proposed. It makes sure that each household may effectively engage in P2P energy trading and profit from low-cost PV electricity by using a set price and energy distribution strategy based on the supply-to-demand ratio. In [143], energy trading at the urban scale is modelled as a recurring game between buildings using a game-theoretic method. Results indicate that solar energy can provide up to 25 % of the electricity demands of the city.

7.1.2. Wind

Wind energy, also referred to as wind power, is the process of generating electricity using wind turbines. Wind energy is a common renewable energy source and an important source of clean energy. Studies on P2P energy trading of wind energy are relatively small compared to solar energy, as residential buildings typically install wind turbines for on-site energy generation. Wind turbines are typically found in microgrid-equipped medium- or small-scale wind farms. A P2P architecture for energy trading in the retail layer for wind power producers is proposed in [144] to encourage the use of wind power and increase its revenue. In [145], a framework for stochastic decision-making is provided wherein a wind power producer uses demand response aggregators to supply some necessary reserve capacity in a P2P system to increase profit for the wind power producer and reduce costs for the aggregators. In [146], P2P energy trading is established in multi-microgrid networks, considering solar and wind energy systems to reduce the overall cost of all microgrids and increase the load on centralized power networks.

7.1.3. Hydrogen

Innovative hydrogen production solutions are possible using

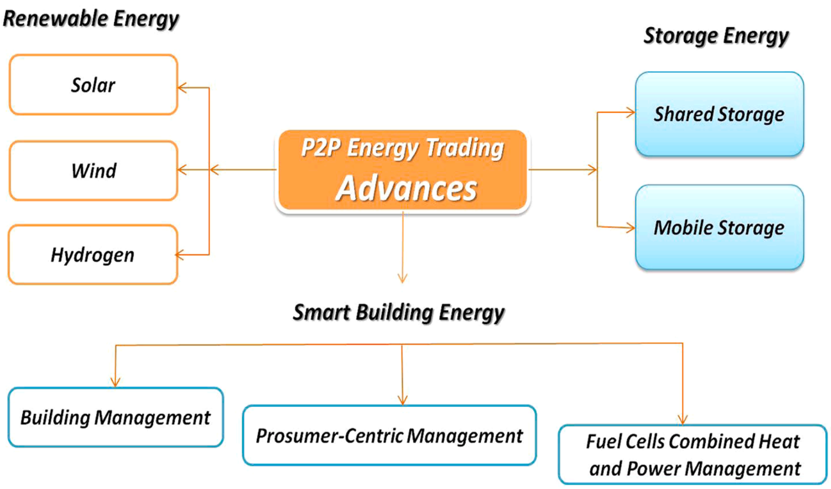


Fig. 5. Different systems in the energy network.

Table 3
Summary of P2P advances in different energy systems.

Energy	System	Summary	Refs.
Renewable	Solar	Create P2P energy trading systems that prioritize residential houses involvement in reducing energy costs, balance demand and supply, lower peak demand, and control losses in the network.	[140–143]
	Wind	Create P2P trading systems that allow participants in interconnected communities to trade wind energy.	[144–146]
	Hydrogen	Investigate the potential of P2P hydrogen trading systems within the energy network.	[147–150]
Smart Building	Building Management	Generate excess energy or decrease energy deficits within buildings to engage in P2P energy trading.	[151–158]
	Prosumer-Centric Management	Generate resources, such as HVAC, lighting, and flexible load control for P2P market trading within buildings.	[159–162]
	Fuel Cells Combined Heat and Power Management	Anticipate buildings equipped with FC—CHP systems will share cogenerated heat and electricity with nearby buildings.	[163–165]
Storage	Shared Storage	Increase the use of storage devices while decreasing the initial investment cost to benefit prosumers and the grid.	[166-170]
	Mobile Storage	Potential components for P2P trading have the ability to move their stored energy to help the grid by enabling flexible demand and control.	[172–174]

renewable energy sources such as solar and wind. When energy from the sun and wind is abundant, electrolyzes can utilize some of it to produce hydrogen, which is then stored for a literal rainy day. The stored hydrogen would subsequently be converted into electricity by turbines to support the grid. Utilizing renewable energy sources to produce hydrogen is an effective way to promote their use and reduce carbon emissions. Researchers are also interested in the possibility of P2P hydrogen trading within the energy network. A P2P electricity-hydrogen energy trading system with a purification sharing system is suggested in [147]. It showed that multi-microgrids can have a 5.50 % reduction in overall operating costs. P2P electricity-hydrogen trading between integrated energy systems is proposed in [148]. The suggested frame's economy and efficacy have been demonstrated. In [149], an optimization model for multi-agent electricity-heat-hydrogen P2P energy trading is presented. Hydrogen is used to blend natural gas and is used in P2P transactions. A cooperative electricity-hydrogen trading model to promote low-carbon travel is proposed in [150]. The electricity-hydrogen trade appears to have advantages over pure electricity coupling.

7.2. Smart building energy

Some buildings are able to generate enough energy to be traded in P2P energy trading. Building systems may use DERs such as HVAC (heating, ventilation, and air conditioning), lights, and flexible loads to control their energy consumption. Prosumer-centric energy management within the building is required to ensure that human convenience and needs are prioritized. Buildings are increasingly utilizing fuel cells and combined heat and power.

7.2.1. Building management

Building management systems (BMS), also referred to as building automation systems (BAS), are computer-based control systems installed in buildings that are used for monitoring and managing the mechanical and electrical systems, such as HVAC, lighting, power systems, and security systems. Building management systems [151] can generate energy excesses or decrease energy deficits within buildings to allow a building to engage in P2P energy trading [152]. Controlling the lighting [153], HVAC [154], and flexible loads [155] is how energy is managed. To enhance community energy efficiency, [156] investigates the coordinated energy management for a community of energy buildings with controllable HVAC systems and renewable energy installations with P2P energy sharing. A P2P energy sharing framework for smart buildings considering multiple dynamic components covering heating, ventilation, air conditioning (HVAC), battery energy storage systems, and electric vehicles is proposed in [157]. The proposed transactive framework can improve the total welfare of smart buildings. In [158], an energy-transactive residence system is created for smart homes with HVAC systems. Results demonstrate that the strategy successfully encourages energy trading between customers to lower peak loads and lower the system's total energy costs.

7.2.2. Prosumer-centric management

Modern electricity markets should be prosumer-centric, as prosumers develop into smart agents capable of producing and consuming energy. Prosumer-centric or human-centric management is characterized by energy management schemes that prioritize human convenience and needs and result in benefits for prosumers. Prosumer-centric building management schemes are closely related to demand response that generates resources for P2P market trading, such as HVAC, lighting, and flexible load control. A new prosumer-centric P2P energy trading architecture that incorporates the export-import restrictions for network security is presented in [159] by integrating prosumers' desires to trade in the market that benefits prosumers and ensuring that networks are operating securely. A grid-connected prosumer-centric residential smart community is proposed in [160], where neighbors with energy deficits can trade, control, and plan excess energy produced by DERs. A prosumer-centric P2P energy community trading model is proposed in [161] that optimize the flow of power between prosumers who have excess renewable energy and prosumers who don't have enough, all while preventing critical grid circumstances and maximizing community welfare. A novel prosumer-centric concept of limit trading is introduced in [162] that aim to increase prosumers' benefits from P2P energy trading while enhancing the community's overall social welfare.

7.2.3. *Fuel cells combined heat and power management*

Combined heat and power (CHP), commonly referred to as cogeneration, is the process of producing electrical energy and useful thermal energy jointly from a single fossil fuel source. Fuel cells use an electrochemical mechanism to transform the chemical energy of a fuel into electrical energy. Fuel cells are utilized for distributed generation (electricity only) and can also be used for combined heat and power (CHP) to provide stationary power. The bulk of these fuel cells are installed in commercial and residential buildings since there is substantial concurrent demand for both thermal energy and electricity in these types of structures. Fuel cells and combined heat and power (FC-CHP) have demonstrated great promise in the context of cogeneration systems for residential and commercial buildings. Despite their relatively high cost, these systems offer many benefits, including high overall system efficiency for both electricity and thermal systems and a reduction in operating electricity costs [163]. Consequently, FC-CHP cogeneration systems have emerged as a further common DER to improve local production and consumption. It is anticipated that buildings equipped with FC-CHP systems will share cogenerated heat and electricity with nearby buildings. A new method for effective energy management in a community of residential demand units equipped with FC-CHP systems and a P2P energy trading platform is proposed in [164] to improve local energy systems' resilience and self-sufficiency. A dynamic heat/power switching method is developed in [165]. It is confirmed that the suggested energy management system, which uses the FC-CHP dynamic switching method, reduces fuel cell degradation and uses less energy.

7.3. *Storage energy*

Storage energy has benefits in terms of rapid response time, temporal and spatial imbalance reduction, and smooth fluctuations. When using a variable energy pricing plan, users using storage can trade energy by charging during off-peak hours and discharging during peak hours. Storage can make energy networks more flexible when used to prevent blackouts caused by natural disasters or systematic failures. Moreover, it can guarantee the steady production of renewable energy. Prosumers depend on their storage to engage in P2P energy trading. With the emergence of electric vehicles, prosumers's decision-making processes are influenced by the need to charge and discharge a large number of mobile storage devices. Prosumers should therefore employ an advanced algorithm for managing their battery storage, which may help them choose which form of storage to prioritize out of all of the available options. Prosumers who sell energy in the P2P market can benefit from its innovative use and earn a larger return on investment by doing so during times of peak pricing.

7.3.1. *Shared storage*

Shared energy storage (SES) is a method to increase the use of storage devices while decreasing the initial investment cost [166]. The sharing can be beneficial to prosumers as well as the grid. A P2P energy trading market mechanism utilizing shared energy storage devices is proposed in [167]. The proposed method guarantees balance, increases efficiency, and reduces energy costs. Central shared battery energy storage, an integrated center with multiple battery units, is considered in [168]. Peers lower their costs by charging and discharging at off-peak and peak consumption hours, maximizing their level of social benefit by engaging in the P2P market. Households can increase their savings by 26.38 % when they employ photovoltaic and storage for energy sharing [169]. Both social welfare and financial gain are enhanced when PV and battery energy storage system sizes are optimized for users [170]. Retailers' costs can be significantly decreased by energy storage [171], and a high degree of matching can be utilized as a factor for selection to maximize the benefits of shared energy storage.

7.3.2. *Mobile storage*

Mobile storage or electric vehicles balance energy supply and demand without affecting the energy networks. They help in reducing greenhouse gas emissions and pollution stack measurements. Electric vehicles charge their batteries from charging stations and supply energy when there is a shortage in the smart city. They also supply their excess energy to the energy networks to meet demand. Local energy trading helps electric vehicles balance the electricity supply and demand during peak hours. As electric vehicles can charge and discharge batteries, their widespread use have the ability to help the grid by enabling flexible demand and control. Electric vehicles are seen as potential components for P2P trading because they have the ability to move their stored energy. P2P energy management systems, considering the vehicle-to-home mode proposed in [172], improve community local consumption, reducing the load on them and the losses of the distribution and transmission networks by lowering the amount of energy shared with the grid; they also lower the cost of operation by utilizing the battery of an electric vehicle as additional energy storage, which eliminates the requirement for more central storage, charging stations, and infrastructure. It's also suggested that [173] electric vehicles can be planned for cooperative applications, such as P2P energy trading and grid-related ancillary services. Electric vehicle energy trade is made possible with the introduction of a coordinated and safe blockchain-based system in [174] to guarantee effective coordination amongst electric vehicles and to enable safe and efficient energy trading.

8. Challenges

P2P energy trading can offer significant benefits to both prosumers and distribution networks. These benefits include increased renewable deployment and flexibility, balancing and congestion management, provision of ancillary services to the main power grid, increased economic performance, increased system efficiency, decreased primary energy consumption and required energy storage capacity, avoided devaluation of energy quality, lessened grid pressure for energy interactions, helping decarbonize society, and facilitating reliable trading with PV prediction error and uncertainty, strengthening the social bonding, demand-supply balance, peak demand shaving, diminishing generation and storage requirement, energy losses minimization, and power network reliability improvement [15,175].

Despite these benefits and recent technological and technical developments, there are still challenges that need to be resolved before techniques that can enable P2P trading in the energy market can be effectively implemented. Fig. 6 and Table 4 provide a summary of these challenges.

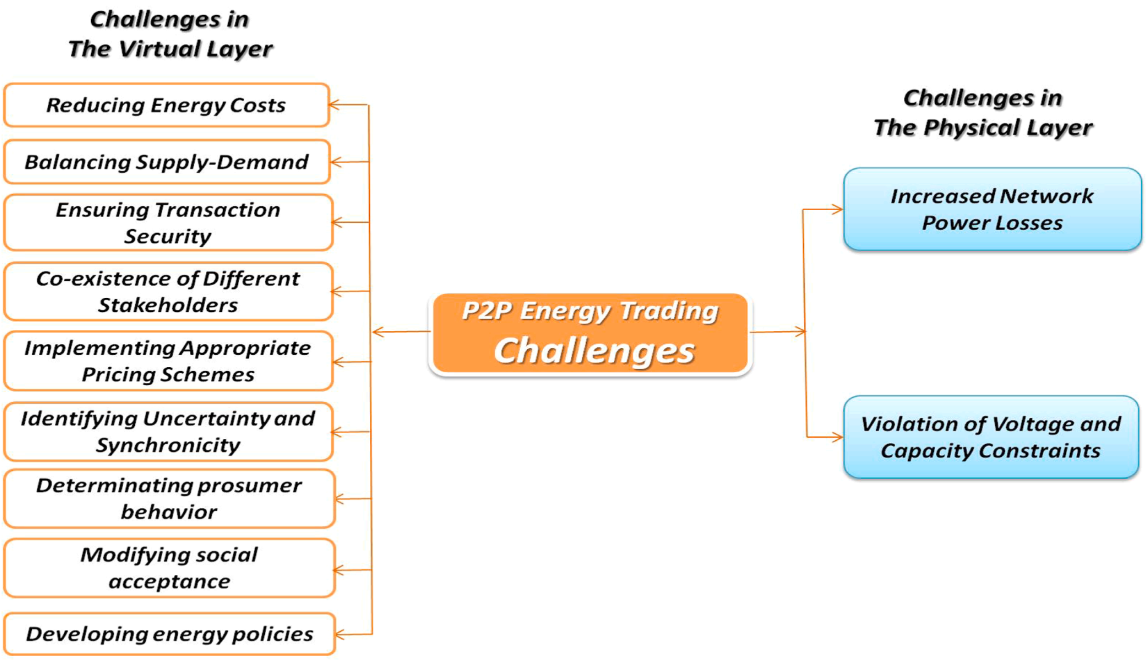


Fig. 6. P2P energy trading challenges.

8.1. Challenges in the virtual layer

P2P energy trading mechanisms should help prosumers achieve lower energy costs by achieving balance in local supply and demand, implementing appropriate pricing schemes, and securing transactions carried out without the need for third-party management. The challenges on the virtual layer platform are as follows:

Reducing energy costs: One of the most important aspects of P2P energy trading that can encourage residential customers to become prosumers is the reduction in energy costs. Prosumers that participate in P2P trading may be able to exchange energy at a price that is higher than the FiT tariff and lower than the price of purchasing from a retailer. As a result, purchasers and sellers can both benefit financially. Extensive participation in P2P trading is a significant contributor to reducing energy costs [176]. However, how much that prosumer can save costs depends upon their individual decision-making processes when it comes to trade [177]. P2P energy trading has been demonstrated to be significant in reducing prosumers' energy costs by allowing small-scale prosumers with DERs to sell their excess energy to prosumers who are facing an energy shortage [178]. P2P energy trading can perform better cost reduction once the batteries used in the system are available on the market [179].

Balancing supply-demand: The ability of P2P trading to enable prosumers to purchase needed energy at a price lower than in the traditional market from prosumers with excess energy is what reduces energy costs. Energy supply and demand in the community must be balanced for such trading to occur. Any imbalance in the local supply and demand might result in system failure, instability, and unreliability [180]. This means that, at a comparatively higher cost, the distribution grid [181], diesel generators [182], or community storage [183] must be used to satisfy the overall energy balance of the P2P network. A ledger that records each transaction and the supply and demand available to each prosumer involved is crucial for supply and demand balance. Prosumers control their own consumption of energy with residential demand response schemes, regarding the energy consumption of different purchasers and sellers, and then trade with each other to keep the community's supply and demand balance by using blockchain-based platforms [184].

Ensuring transaction security: Financial transactions between prosumers need to be done securely to take part in P2P energy trading. The ability of blockchain to provide reliable and secure transactions makes it the most suitable trading platform [185]. The provision of blockchain-based secured trading transactions is extremely computationally costly [186]. It will require a large amount of energy to service participants if such a costly computing technique is adopted. Participants will therefore share the costs of this service, which will increase the cost of trading. Thus, for a wider adoption of P2P energy trading, new and computationally less costly technologies will be needed to ensure the market's abilities in terms of cost, security, and trust.

Co-existence of different stakeholders: Making decisions about energy trading is difficult because of the involvement of parties such as generators, distributors, and retailers who have competing interests in utilizing prosumers' energy. Different stakeholders would be willing to utilize prosumers' batteries to maintain network security and provide various services to their users [187]. Generators may need to involve them to reduce generation instability; distributors may need to involve them to reduce demand constraints; and retailers might have to discharge the batteries to address energy unbalances, which might result in contradictory actions. Thus, techniques for implementing P2P energy trading need to be developed for use in systems where stakeholders co-exist with other network parts without influencing one another's roles or interests within the network.

Implementing appropriate pricing schemes: The financial transactions among the trading participants enable significant number of prosumers to participate in P2P energy trading. Prosumers should control their energy-related operations or their energy consumption [188]. Prosumers may therefore find it difficult to generate enough energy for the network as a result of these possible outcomes. For prosumers to be encouraged to participate in energy markets, appropriate pricing schemes are required to return such a burden. An appropriate price scheme should be introduced to guarantee appropriate and incentive-compatible income for P2P energy participants.

Identifying uncertainty and synchronicity: Although P2P energy trading can help customers by offering a variety of energy services, consumer engagement, and lower transaction costs, the results of the trading may not be ideal if the prosumer engagement and negotiation are inadequately organized because of insufficient forecasting, a lack of transparency and comprehension of network conditions, a lack of

Table 4
Summary of P2P energy trading challenges.

Layers	Challenge	Summary	Refs.
Virtual layer	Reducing energy costs	To reduce prosumers' energy costs by allowing small-scale prosumers with DERs to sell their excess energy to prosumers who are facing an energy shortage.	[176–179]
	Balancing supply-demand	To balance supply and demand within the community, prosumers should be able to control their own consumption of energy and then trade with each other.	[180–184]
	Ensuring transaction security	To enable prosumers to participate in P2P trading in securely financial transactions.	[185,186]
	Co-existence of different stakeholders	To develop techniques for implementing P2P energy trading where stakeholders co-exist with other network parts without influencing one another's roles or interests within the network.	[187]
	Implementing appropriate pricing schemes	To develop suitable and unbiased pricing schemes in order to guarantee appropriate and incentive-compatible income for P2P energy participants.	[188]
	Identifying uncertainty and synchronicity	To deal with operational uncertainties, to identify computing and communication complexity problems.	[189]
	Determinating prosumer behavior	To create a system that will benefit prosumers in order to involve them in P2P energy trading. The success of trading depends on individuals' desire to participate in these markets.	[16,26,36,190,191]
	Modifying social acceptance	To create social trust of P2P energy trading in the community to improve transparency, reduce fraudulent transactions, and increase a sense of attachment to that community.	[19,192,193]
	Developing energy policies	To regulate the P2P trading market in order to guarantee its viability. Prosumers should be allowed and encouraged by the government.	[194–198]
Physical layer	Increased network power losses	To consider power loss in the P2P trading network and subsequent cost allocation between prosumers.	[199–201]
	Violation of voltage and capacity constraints	To prevent overvoltage and reverse power flow problems in distribution networks by introducing P2P trading and improving the voltage profiles.	[202,203]

customer information, or communication delays. When a significant number of prosumers participate in P2P energy trading, the computing and communication complexity problems must be managed to ensure the system operates reliably [189]. Advanced techniques should be employed to differentiate between the network conditions for every P2P trading period, and accurate forecast techniques should be applied. Prosumers should be informed about the benefits of P2P energy trading and the need to inform the market of their generation and demand.

Determinating prosumer behavior: P2P energy markets consist of small-scale energy producers who use their DERs to benefit the community; the success of P2P energy trading depends on individuals' desire to participate in these markets [26]. P2P applications, however, are vulnerable to an attitude-behavior gap since individuals' expressed positive attitudes may not always correspond with their actual adoption of these systems [36]. According to [16], consider that one of the primary challenges facing P2P energy trading is the absence of prosumer participation. Early research on this issue indicates that 79 % of 830 participants in Europe are in favor of P2P energy trading participation [190], while 77 % of participants in an online experiment actively participate in P2P trade decisions [191]. Although these theoretical results are encouraging in terms of potential prosumers' adoption of P2P energy trading, empirical research on prosumer behavior in P2P energy trading requires concrete case studies and pilot testing of practical applications. P2P energy trading is a more complex case because its participants need to have a basic understanding of both the economic and technical aspects of DER generation (such as the balance of supply and demand, electricity prices, network tariffs/transaction costs), as well as the impact of weather, production times during the day, and self-consumption optimization. P2P energy trading consequently depends on how well their user interface satisfies actual prosumer needs in order to encourage additional adoption of DERs.

Modifying social acceptance: Since P2P energy trading is typically used to facilitate local energy trade, the trading platform must take into account community values, problems, and social justice issues in addition to market-driven trading. Research conducted in Australia as part of the Water Nexus and renewable energy project revealed that participants expressed dissatisfaction with the excessively market-driven trading design and wished to be able to choose suppliers and sell to specific members of the community. As part of the pilot to show off the benefits of P2P energy trading in the community, participants consented to pay more in the P2P scheme with the hope that this would eventually result in lower costs. P2P energy trading platforms ought to feature an easy-to-use interface, just like other modern technologies have been adopted. A platform that has an intricate trading mechanism or user interface may make it more difficult for users to join the trade. There is still a lack of social awareness and acceptance of the P2P energy trading concept [192]. Given that P2P energy trading is an innovative approach to trading local electricity in addition to the introduction of new technology, establishing confidence amongst stakeholders in the new technology adoption is a critical concern [193]. Furthermore, the adoption of the P2P model is expected to impact the local community's lifestyle and cultural practices regarding the supply and demand of electricity. A social trust should be created to improve transparency, reduce fraudulent transactions, and increase a sense of attachment to that community [19].

Developing energy policies: Prosumers are an important part of P2P energy trading, so before implementing P2P energy trading, the government should first permit and support prosumers. P2P energy trading is likely to be implemented in countries where policies to support prosumers are certain, such as Germany [194], the Netherlands, and South Korea [195]. All prosumers in Germany and the Netherlands are permitted by regulations to sell electricity [196], in contrast, prosumer promotion is part of the national policy in South Korea [195]. In terms of the effective use of renewable energy resources, the government can promote the growth of P2P trading.

P2P energy trading is not as widely implemented as it could be due to regulations and policies that are not keeping up with technological advances. In order to plan for infrastructure investments and implement the required regulatory changes, authorities and policymakers should be fully aware of the benefits and implications of the P2P energy trading models. Furthermore, it's critical to align the P2P energy market with the existing policies, which call for defining acceptable market designs, the distribution of taxes and fees, and the connection between P2P energy trading platforms and conventional electricity markets. There are several risks and complications associated with integrating the P2P model into the public grid infrastructure [197,198]. This is because it is not evident if P2P energy trading is the ultimate goal of the electricity market or merely one of the business models operating within the existing framework. Local, microgrid, or P2P energy markets would first need to be incorporated into the existing regulatory framework. They could, however, significantly change the established roles that entities play in the current market framework. Clearer ownership and partnership arrangements, prosumer licensing, related regulations, and market responsibilities are just a few of the specifics that need to be addressed regarding the direction of policy development in P2P energy trading.

8.2. Challenges in the physical layer

Once the parameters for energy trading are determined on the virtual layer, the actual transfer of energy takes place over the physical layer. If the decision-making process on the virtual layer platform ignores the impact of P2P trading on the physical layer platform, the transfer of energy could violate certain technological restrictions. Challenges that could prevent energy transfer over the physical layer platform are as follows:

Increased network power losses: P2P energy trading causes a rise in node voltages and overloads the network due to the energy transfer between participants, resulting in losses leading to excess energy amounts and costs that exceed the net demand for each market entry that must produce and recover [199–201]. This will increase energy costs for purchasers. Retailers are now able to sell electricity at a lower cost than before because of the network's connection to a significant number of renewable energy plants. This could have an impact on P2P trading costs. Therefore, the loss factor needs to be allocated within the trading cost while remaining competitive. It is difficult to directly regulate the flow of electricity, and the seller will provide energy to the intended customer through the distribution network. This would result in a different power loss than if the purchasers received the seller's energy supply. Thus, an investigation to calculate the actual loss and decide the P2P trading price is needed.

Violation of voltage and capacity constraints: Prosumers may actively participate in P2P energy trading, but because they are connected to LV distribution networks, they are susceptible to overvoltage and reverse power flow [202]. The load on the inverters would increase if large-scale energy transactions were conducted over the P2P network, which is primarily in charge of supplying energy to the network after they are installed inside prosumers' buildings. This might be minimized by employing network voltage balancing methods for smart PV inverters in view of distributed optimization and P2P connections [203]. Operational overhead, which may increase energy transfer costs since it requires a lengthy chain of maintaining many blocks, is another potential consequence of pushing energy by several prosumers in the network. The network's safety and security will be compromised by the unchecked power injection from all prosumers. Controlling the amount of energy that each prosumer is permitted to send to the network within a given time, however, may be a method for reducing this risk. On the other hand, forcing such unbending limitations on prosumers' decisions may have a negative impact on the possible income they could anticipate from trading, which might discourage prosumers from participating in the future.

9. Future research directions

P2P energy trading is one of the emerging and popular research areas in the field of smart grids, as is evident from the research works and real-world use cases. The researchers have made a lot of progress in this direction, and much more needs to be done. Here are some research directions based on P2P energy trading [15,20,32], which are described as follows:

- ***P2P energy trading:*** Most power systems in traditional energy trading are controlled by a central authority, leading to a single point of failure. P2P energy trading is therefore necessary, allowing traders to exchange electricity in any direction based on supply and demand for energy.
- ***Inter- and intra-community trading:*** Energy producers have the right to choose for themselves whether they want to trade energy with consumers in an intercommunity or intra-community. Policies and methodologies are also required in the energy market to solve this confusion and provide prosumers with such flexibility.
- ***Large-scale network trading:*** Given that P2P trading has the proven ability to significantly increase prosumers' financial profits, a significant number of prosumers may express interest in participating in P2P markets. Therefore, it is necessary to investigate how widespread prosumer participation affects the distribution network constraints. To determine the complexity of the distribution network in great detail, a large-scale P2P trading trial—which has never been done before—can be carried out in real residential areas with considerable prosumer participation.
- ***Benefit to the grid:*** The value provided by prosumer-centric P2P trade to the distribution grid is not clearly stated in the current literature. In reality, if necessary, provisions can be made to enable the grid to participate in the P2P market as a power supplier or as a service provider. Also, additional regulations can be added to the P2P trading systems to prevent financial losses for the grid.
- ***Cost-efficiency:*** Prosumers can trade electricity for consumers at higher costs to increase their profits. P2P energy trading, therefore, necessary in order to give prosumers and consumers a dispersed platform where they can both profit equally. In order to guarantee optimal energy costs during P2P energy trading, a number of methods are also employed, such as game theory.
- ***Network security:*** Energy exchange and associated information and financial transactions between P2P trading participants may be exposed to many attacks. P2P trading based on blockchain ensures network security and offers transparency and security against attacks.
- ***Data privacy accessibility:*** Data privacy in the distribution network is an important issue, as this data may be used in a variety of applications for data analysis and prediction. P2P energy trading based on blockchain technology is an effective solution to guarantee secure data sharing, security, and privacy for both prosumers and consumers.
- ***Multi-level storage management:*** There are various types of storage facilities available to communities using P2P trading. These include small batteries for smart home users, medium storage at the community level, and high storage at the grid level. Therefore, there is a need for social and economic coordination among these storage devices at all levels. Also, P2P energy trading requires optimization techniques for storage management.
- ***Prioritizing different stakeholders:*** There may be conflicts of interest among the stakeholders. For instance, P2P trading can be utilized by power suppliers, network operators, and retailers to reduce output volatility and address demand constraints and power imbalances in the distribution network. Therefore, more research is needed to prioritize different stakeholders according to distribution level.
- ***Business models:*** P2P energy markets present a promising opportunity for energy traders, who need to investigate methods to improve their current offerings. Encouraged P2P energy trading in their local markets presents an opportunity. The business models for this type of digital transformation are not extensively researched.
- ***Techniques development:*** The techniques found in the body of current literature do not ensure that P2P prosumers will fairly limit the amount of power they export. Therefore, the suggested techniques can be expanded by adding a fairness factor for determining the amounts of P2P power exports between prosumers in distribution

networks. To encourage prosumers to get more involved, unbiased demand increases and decreases for P2P trading might be performed.

- ***Inclusion of network constraints:*** P2P energy trading implementation can result in increased power injections and draws at the nodes of the distribution network. These energy transactions may result in voltage fluctuations and line limit violations if they are permitted without considering the network parameters. The P2P energy trading systems should be developed with the network constraints.

10. Conclusion

Peer-to-peer (P2P) energy trading is a novel paradigm that enables direct energy trading between prosumers and consumers in electric power systems with a high penetration rate of DERs. This can help with local energy balancing and potentially improve bulk power network operation. This paper provides a review of existing P2P energy trading in order to identify areas of recent research development and learn about the challenges that are keeping P2P from becoming a viable energy management solution in the present electrical market. A P2P energy network, P2P energy trading types, and P2P market structures have been introduced initially. The technologies and technical approaches that support P2P energy trading are discussed in detail. P2P advances in different systems were then introduced. We have finally identified challenges and future directions.

CRediT authorship contribution statement

Mona Zedan: Writing – original draft, Visualization, Resources, Investigation, Formal analysis, Data curation. **Morsy Nour:** Writing – review & editing, Supervision. **Gaber Shabib:** Writing – review & editing, Supervision. **Loai Nasrat:** Writing – review & editing, Supervision. **Al-Attar Ali:** Writing – review & editing, Supervision.

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.

There's no conflict of interest

Data availability

No data was used for the research described in the article.

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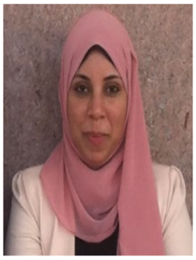

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