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TOPICAL REVIEW

Bridging theory and practice in peer-to-peer energy trading: market mechanisms and technological innovations

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Abstract

The article provides a synthesis of the literature on the peer-to-peer (P2P) energy trading paradigm. P2P energy trading is a prosumer business model and a transformative concept that allows prosumers to sell surplus generation to other prosumers and consumers within an energy community or microgrid. P2P energy trading is a novel concept to promote decentralization, decarbonization, democratization, digitalization, and enhancing energy resilience of the energy sector. The article covers different facets of P2P energy trading, including market designs, changing actor roles, pricing mechanisms, enabling technologies, and challenges. The article thus addresses emerging and complementary aspects not covered in prior literature reviews. As such, three market designs are discussed: centralized, decentralized, and distributed, and four pricing mechanisms, which are optimization, game theory, auction-based, and reinforcement learning. Enabling technologies discussed are Energy Internet, Internet of Things, Artificial intelligence, Blockchain, Communication networks, and battery flexibility. The paper discusses the challenges that the development and commercialization of the P2P energy trading faces—especially focusing on the social ontology of the concept—and provides research directions to amplify the scaling up of the technology.

1. Introduction

The global ambition for a carbon-free future and evolution in technological, social, political, institutional, and cultural agendas have led to the disruption of the energy sector and promoted a reconfiguration in the way energy is being produced, distributed, and consumed (Delina and Janetos 2018). One such disruptive reconfiguration occurring in the electricity sector is the emergence of the peer-to-peer (P2P) electricity trading paradigm, which is fueled by the exponential diffusion of Distributed Energy Resources (DERs) such as solar PV and battery energy storage systems (BESS). P2P energy trading is a market-driven prosumer business model that enables owners of DERs (called prosumers, which are households and buildings with electricity generation and storage assets) to sell surplus generation to other prosumers and consumers in localized energy markets or within community energy groups. By leveraging technologies such as smart grids, Internet of Things (IoT), data analytics, and artificial intelligence, P2P energy trading facilitates decentralized energy transactions via a digital energy marketplace, thus advancing the principles of decentralization, digitalization, decarbonization, and local energy autonomy (Tushar *et al* 2021b).

The attractiveness of P2P energy trading lies in its potential to foster consumer engagement and promote sustainable energy practices by supporting innovative, behind-the-meter flexibility activities and redefining traditional energy production and consumption matters (Wu *et al* 2022). P2P electricity trading aligns closely with the 'Energy Internet (EI)' concept, where digital platforms and smart grids interconnect producers, consumers, and BESS, enabling dynamic, autonomous trading of renewable eletricity at the grid edge, that is, the interface between the grid and distributed end users (Hussain *et al* 2019). This digital infrastructure, combined with the community-driven focus of Community Energy projects, empowers local groups to generate, manage, and trade renewable energy, building resilience and reducing dependence on centralized power systems. By enabling communities to benefit from shared renewable energy resources, these concepts collectively create new economic opportunities in the renewable energy sector, enhance local autonomy, and offer a participatory, sustainable approach to energy transition.

The literature on P2P energy trading has grown extensively in recent years, attracting interdisciplinary attention across engineering, economic, legal and policy, and sociocultural aspects (van Soest 2018, Tushar *et al* 2021b, Schneiders *et al* 2022). While the body of research has expanded considerably, certain critical aspects of P2P energy trading remain insufficiently examined, leaving opportunities for further exploration. Given the significant interest from industry and academia, this review seeks to address complementary and emerging aspects that remain underexplored. Specifically, the article focuses on the driving factors that have pushed for a re-orientation of the electricity supply system at the grid edge, different market designs for P2P, evolving actor roles within the energy system, pricing mechanisms with particular emphasis on their mathematical formulations and enabling technologies that enable the implementation of P2P energy trading. By addressing these areas, this review contributes a more nuanced understanding of the challenges and opportunities shaping the future trajectory of P2P energy trading, catering to the growing interest from both industry and academia.

2. P2P electricity trading: concepts and market designs

2.1. The emergence of a new resolution

In the past two decades, state-supported schemes such as feed-in tariffs and net metering have promoted the diffusion of DERs—rooftop solar PV in particular—and guaranteed a benefit to prosumers who export surplus generation to the grid. However, these schemes are now facing challenges, making way for a new resolution in the form of P2P electricity trading. Several countries including India, the U.S., Australia, Germany, and Canada have discontinued their net metering or feed-in tariff schemes (Leiren and Reimer 2018, Soto *et al* 2021). Under feed-in tariffs, the profitability of rooftop solar PV was determined by factors such as roof orientation, geographic location, solar power yield, savings in electricity bills, and revenue generated when surplus generation was exported to the grid. Similarly, net metering schemes enabled the profitability of solar PV by providing higher savings on electricity bills through credits received by exporting electricity to the grid (Schopfer 2019). Declining installation and operational costs of solar PV systems have prompted policymakers to revise or phase out these programs, which contributed to efficient DER utilization by allowing the grid to act as a storage buffer for surplus generation (Schopfer 2019). However, from the perspectives of utilities, the increased integration of DER systems has contributed to the so-called ‘utility death spiral disease’—more DERs, resulting in fewer paying customers to maintain the operations of the grid which in turn, require higher electricity prices and encouraging more DERs in return (Felder and Athawale 2014). Both schemes essentially function as subsidies, deemed unsustainable in the long term (Felder and Athawale 2014).

With fewer financial incentives now available, prosumers must increasingly choose between maximizing self-consumption or investing in more BESS which compromises the financial gains of owning a DER unit. In both cases, amortizing solar PV costs and enabling optimal utilization proves challenging without these policy reinforcements. In response, a resolution to re-establish a mechanism that can support power system services as well as increase prosumer benefits thus lies in the form of an open market for distributed renewable energy generation, where prosumers can sell their electricity directly to consumers, and prices set by demand and supply, paired with some form of minimum service charge to utilities (Martin 2016). This mode aligns with the broader ‘sharing economy’ concepts behind platforms like Airbnb and Uber, which involve consumers granting others access to their underutilized assets against payment. In P2P electricity trading, the value proposition is similar: prosumers monetize the excess capacity of their DER asset at risk of being underutilized (Frenken and Schor 2017, Fell 2021).

2.2. Overview of the P2P energy trading

P2P electricity trading enables prosumers to trade and share electricity with consumers or prosumers within an energy community (Zhou *et al* 2020) or a microgrid. P2P energy transactions are primarily accounting transactions and an agreement between two parties (or peers) rather than the actual buying and selling of a unit of electricity. Electricity is a physical phenomenon and once electricity is exported to the grid or microgrid, it is indistinguishable. The grid also has to be balanced which means that demand and supply should be equal (van Soest 2018). At the basic level, P2P electricity trading is about ensuring the balance such that, when one peer commits himself or herself to export a certain amount of electricity to the grid, another peer commits to buying it (van Soest 2018). Prosumers have surplus solar generation based on their household load profile and commit to selling the generation to other peers within the microgrid. Although electricity is a homogeneous product, P2P electricity trading introduces competition through elements like specific trading partners, discounted prices, local generation, and grid-supplied electricity based on the source, effectively transforming it into a heterogeneous product. Consumers thus gain the flexibility to choose based on their preferences, enhancing investment security for prosumers by creating a revenue stream independent of policy support. This system operates within a low-voltage microgrid or distribution network where utilities or grid operators can charge rent for transmission line usage (Schopfer 2019, Soto *et al* 2021). P2P electricity trading promotes a win-win outcome: prosumers earn revenue as sellers of electricity, often at prices higher than utility tariffs, while consumers benefit from renewable energy at market-driven prices, typically lower than utility tariffs near the point of generation.

P2P electricity trading offers multiple advantages and prospects for energy transition and enhancing grid resilience. It reduces the need for intensive energy storage capacity (Hirvonen *et al* 2014), supports solar energy adoption with minimal power distribution losses (Azim *et al* 2020), relieves grid pressure, and helps to maintain energy quality (Neves *et al* 2020). The P2P energy trading business model can promote community energy projects and transform the centralized fossil fuel-dependent grid by supporting DERs and accommodating renewables like wind and solar despite their intermittency. P2P energy trading is also expected to develop the environmental conscience and make more informed prosumers and consumers as they experience the energy production and consumption process more closely (Giotitsas *et al* 2015, Parag and Sovacool 2016). Values like social cohesion and a sense of community can be leveraged (Jogunola *et al* 2017). With rising DRE adoption, P2P energy trading can decentralize economic-political power by allowing prosumers to provide ancillary services to the grid by coordinating DERs, forming virtual or federated power plants (Giotitsas *et al* 2015, Morstyn *et al* 2018). In remote and underserved regions, P2P energy trading offers opportunities for 'swarm electrification', where prosumers can supply surplus generation to unelectrified households. It thus provides a pathway to expand electricity access in rural areas in countries like Bangladesh and Nepal (Khan 2019, Kirchhoff and Strunz 2019, Shrestha *et al* 2019) and contribute to energy development in emerging economies like China (Uhde 2022), Thailand (Junlakarn *et al* 2022), and Malaysia (Heng *et al* 2022). For these reasons, P2P energy trading is poised to transform the electricity sector, as demonstrated by numerous pilot projects exploring commercialization potential. Table 1 provides a summary of existing P2P electricity trading projects.

In practice, P2P electricity trading operates through four strategic layers as shown in figure 1. The virtual layer is the top layer based on a secure information system that enables consumers and prosumers within distribution network to connect, view energy-related information, match expectations, execute agreements, and access financial settlements. It is the user interface, often described as an Energy Management System, that communicates with the prosumer or consumer among other involved parties in the trade. Project developers are building interfaces like web-based or mobile applications to execute this process. The second layer is the business layer which functions as a decision-making hub, hosting an energy marketplace that utilizes algorithms to execute pricing calculations, demand forecasts, electricity transfers, and financial settlements based on user inputs. The functions of the business layer work according to the type of market designs and pricing mechanisms. The third layer is the control and ICT layer which allows seamless communication among all trading entities and the physical network through standardized protocols and communication devices, facilitating efficient trade operations. Once the control and ICT transmit information to the physical layer, the electricity transfer operation is executed. The physical layer is responsible for battery power discharge, monitoring, and metering and is equipped with all the infrastructure at the consumers' and prosumers' premises for electricity transfer to take place. Key to the physical layer is a transactive meter that records all transactions to be accessed and viewed on the mobile or web-based application (Mengelkamp *et al* 2018, Abrishambaf *et al* 2019, Orsini *et al* 2019, Azim *et al* 2020, Suthar *et al* 2023).

2.3. Market structures

There are three primary market configurations for P2P energy trading, each defined by varying levels of centralization, level of autonomy, and peer interaction with each other: centralized, decentralized, and distributed. Table 2 summarizes the strengths and weaknesses of each market design.

In a *centralized* P2P trading market (figure 2(a)), a coordinator (or community manager) oversees all transactions within an energy community or microgrid. The coordinator acts as a middle entity between a prosumer and another prosumer or consumer as well as between the microgrid and distribution network or external markets (for example, wholesale markets). Responsibilities of the coordinator include communication of information and control, overseeing electricity trading, managing shortages within the

Table 1. Overview of a few P2P electricity trading projects (Compiled from Park and Yong 2017, Wongthongtham *et al* 2021, Gunarathna *et al* 2022).

Project Name	Country	Network reach	Start year	Type of project	Customer segments	Objective(s)
Power Ledger	Australia	National and Regional	2016	Real-world trial	Varied—consumers, prosumers, buildings	P2P electricity trading platform using blockchain. Providing multiple digital distributed services
SOLShare	Bangladesh	Microgrids	2015	Real-world trial	Consumers and prosumers (households)	IoT-based P2P electricity trading within microgrids
Energo Labs	China	Microgrids/ Community		Development	Consumers and prosumers	Blockchain-based P2P electricity trading with VPP, V2G abilities
Pebbles	Germany	Community /nanogrid	2018	Real-world trial	Consumers and prosumers (buildings)	Blockchain-base P2P energy trading with VPP
Sonnen Community	Germany	National	2015	Real-world trial	Consumers and prosumers	P2P electricity trading with storage facilities and VPP capabilities
Vandebron	Netherlands	National	2014	Real-life	Consumers and prosumers (commercial)	Provides a P2P electricity trading platform from suppliers' perspectives
Suncontract	Slovenia	National	2016	Real-world trial	Typical consumers and prosumers	Blockchain-based (Ethereum) P2P energy trading platform
Elblox	Switzerland	Community	2017	Development	Consumers and prosumers living nearby	Blockchain technology for P2P energy trading among users living nearby
Quartier strom	Switzerland	Community	2020	Real-world trial	Typical consumers and prosumers	Blockchain-based technology for P2P energy trading
Lumio Solar	Spain	Community	2020	Development	Consumers and prosumers (buildings)	Exchange platform between buildings and households
Piclo	UK	National	2014	Real-world trial	Independent renewable energy suppliers with commercial customers with large energy demand	Marketplace for operators to procure flexibility and users to buy and sell flexibility
Brooklyn Microgrid	USA	Microgrid	2015	Real-world trial	Consumers and prosumers within a microgrid (including businesses)	P2P electricity trading within a microgrid
Power2Peer	USA	Microgrid	2018	Development	Consumers and prosumers	Blockchain-based P2P electricity in a marketplace

community, and additional purchases from external markets, and handling financial settlements. The coordinator collects and redistributes the revenue through a set of predefined rules hence, ensuring social welfare is maximized (Zhou *et al* 2020, Tushar *et al* 2021b). Uncertainties over consumption and prosumption can be minimized as operational control and decision-making is within the purview of the

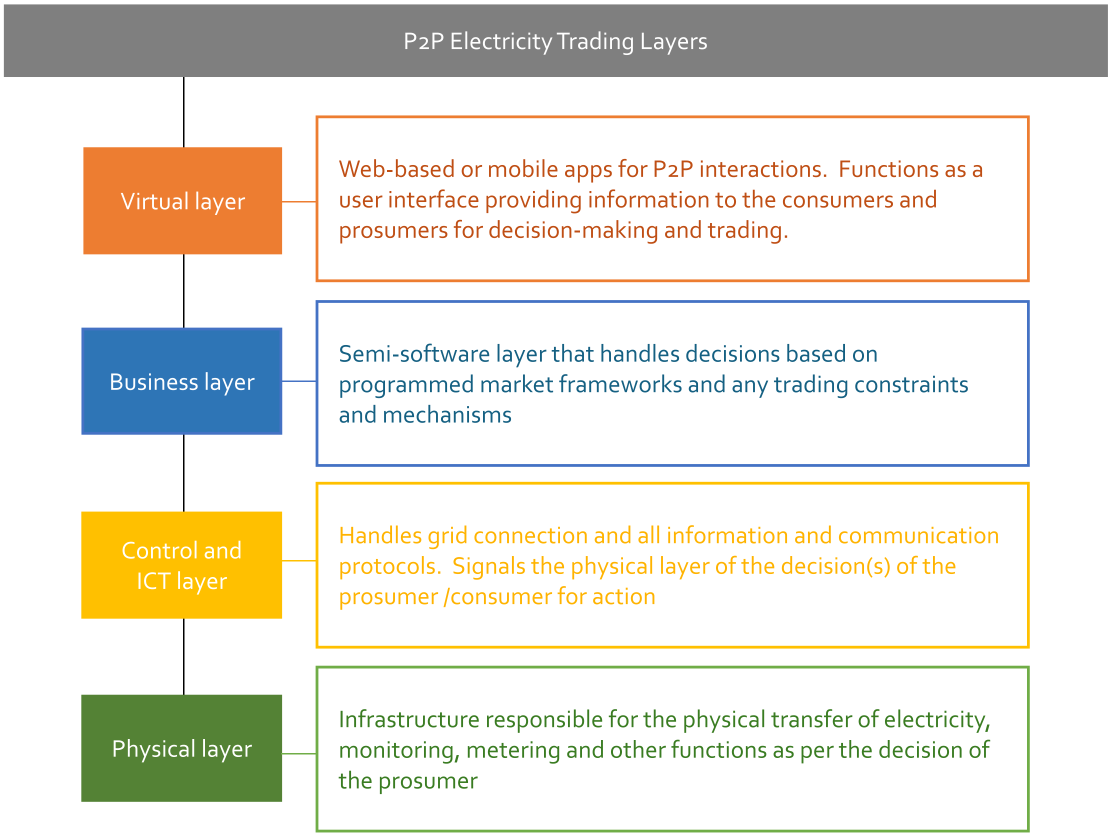

Figure 1. Layers of the P2P electricity trading.

Table 2. Strengths and weaknesses of the market designs.

Market design	Strengths	Weaknesses	References
Centralized	(1) High market efficiency and social welfare (2) Safe market operation via platform operator (3) Uncertainties over demand and supply minimized	(1) Limits peers' autonomy (2) High communication burden (3) Concerns over peers' privacy (4) Single point of failure	Long *et al* (2018), Lüth *et al* (2018), Alam *et al* (2019), Liu and Li (2022), Xia *et al* (2023)
Decentralized	(1) Complete freedom to trade between peers (2) Preserve peer's privacy and autonomy (3) No single point of failure (4) Increases energy awareness	(1) Lower market efficiency and social welfare may not be guaranteed (2) Slower convergence to consensus within reasonable timeframes (3) Potential network security issues	Alvaro-Hermana *et al* (2016), Kang *et al* (2017), Liu and Li (2022), Xia *et al* (2023)
Distributed	(1) Uncertainties between demand and supply minimized (2) Preserves privacy and autonomy (3) Maximizes community benefits via price signals	(1) Fair sharing of energy among the community not guaranteed	Paudel *et al* (2019), Xia *et al* (2023)

coordinator. From a participant's viewpoint, the trading practice becomes 'automatized' as the trading operation duties are devolved to the coordinator, reducing barriers to market entry by allowing peers to outsource trading responsibilities (Heo *et al* 2021). However, this market design faces challenges with scalability, high computational demands, and potential compromise over peers' privacy, autonomy, and security as they share information with a single entity. Studies have tested the efficiency, economic benefits,

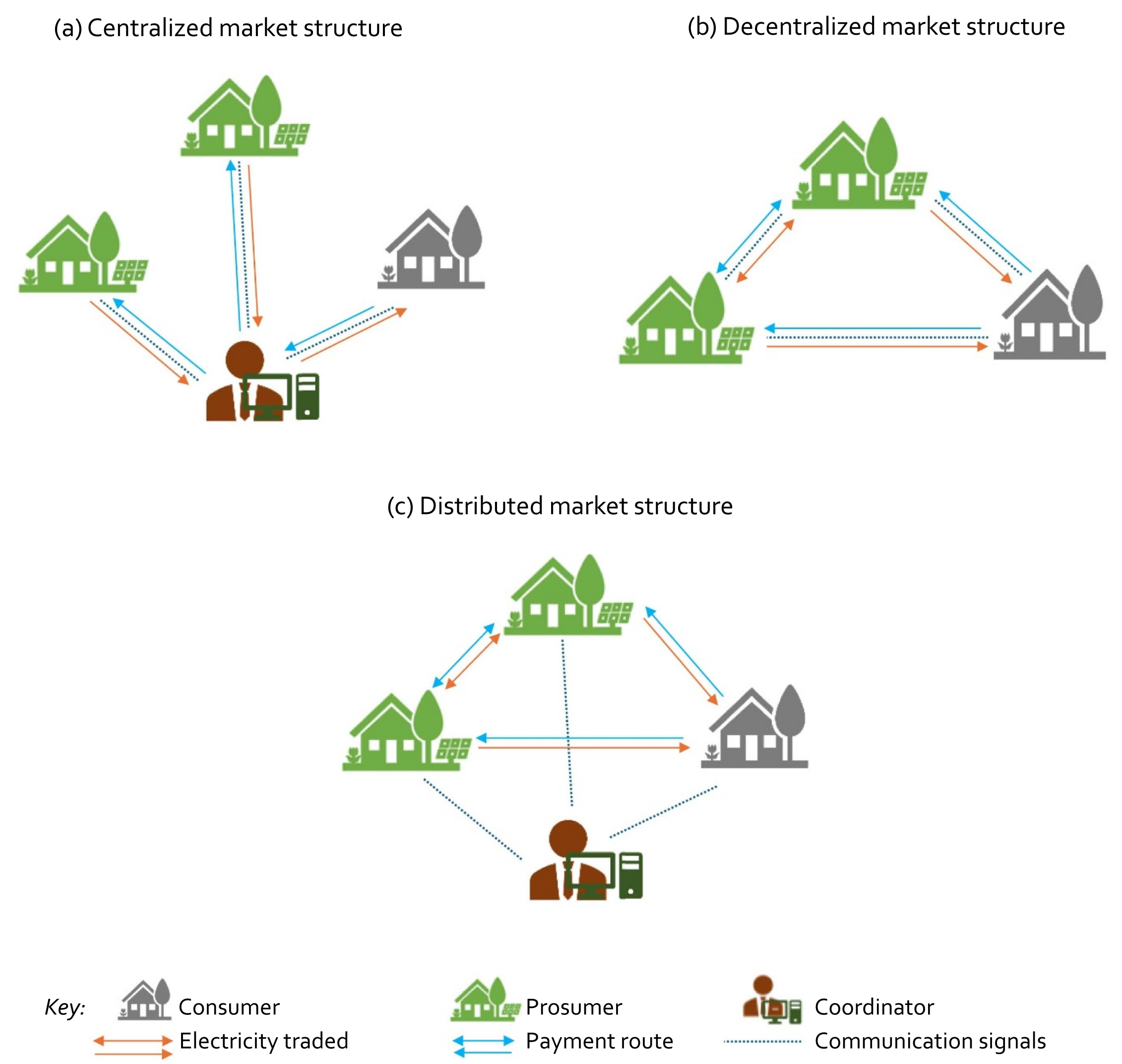

Figure 2. Categorization of P2P energy trading market structures, (a) Centralized market structure, (b) decentralized market configuration and (c) distributed structure.

and potential improvements of the centralized P2P trading market which include Heo *et al* (2021), Lüth *et al* (2018), Nguyen *et al* (2018), Moret and Pinson (2018) and Long *et al* (2018). Coordinators are conventional intermediate running by manpower but recently, Alam *et al* (2019) proposed an algorithm called ECO-Trade that can coordinate trading in smart homes and automate decision-making processes.

The *decentralized* market scheme (figure 2(b)) allows peers to directly trade electricity and execute financial settlements with one another within the connected community without supervision from a coordinator. There is a mutual agreement between prosumers and other prosumers and consumers over the price and quantum of energy to be shared, with communication of information occurring in a completely decentralized fashion (Sousa *et al* 2019, Tushar *et al* 2021b). The advantages of the decentralized market design include greater decision-making powers for prosumers, full control over their devices, and privacy protection being maintained due to the absence of interaction with any third party (Bukar *et al* 2023). However, without centralized coordination, the efficiency of decentralized markets is low. Negotiations over price and quantity for the trade can lead to slow convergence to obtain a consensus within a reasonable timeframe. Additionally, the behaviors of peers over trading strategies vary which is challenging to grid operators, compromising their ability to supply high-quality electricity to all consumers and prosumers within the community (Sousa *et al* 2019). The workability of a decentralized market has been tested by Esmat *et al* (2021), Devine and Cuffe (2019), Sorin *et al* (2019), and Lyu *et al* (2021) among other researchers.

A *distributed* market scheme combines aspects of centralized and decentralized configurations (figure 2(c)). Here, a coordinator provides support but does not directly participate in trading; instead, they function as a communicator and instigator, communicating with peers and using price signals to encourage trades. Hence the coordinator does not have control over the devices of peers maintaining their autonomy and privacy but manages and influences peers' decision-making processes, aligning demand and supply within the community. The coordinator can also interact with the grid and other existing energy markets to maximize P2P trade within the microgrid, minimizing power purchases from the grid, and avoiding energy imbalances. While still holding decision-making powers, the behavior of prosumers can be better understood and coordinated by the coordinator, reducing predictability over potential demand and supply needs through the grid. Fair trading to meet the requirements of all peers is however not guaranteed. Distributed market designs thus provide a balanced solution, offering some of the efficiency benefits of centralized markets with the autonomy of decentralized models (Zhou *et al* 2020). Examples of a distributed market can be found in Paudel *et al* (2019) and Wang *et al* (2022). Zepter *et al* (2019) also developed the Smart elecTricity Exchange Platform (STEP), a digital coordinator for managing trades between a microgrid and wholesale market.

2.4. Market actors and their changing roles

As new types of energy market design emerge, new market actors are introduced while the roles of traditional actors are challenged or redefined. Typically, there are three main actor categories in a P2P energy market that affect or are affected by the trading practice, which are: peers, platform operators, and retailers. Peers and platform operators represent new roles introduced by the P2P market structure while the role of retailers requires adaptation.

(a) Peers

Peers are the primary participants in the P2P energy trading market and can take several roles. A 'peer' can be an individual prosumer, a 'pure' consumer (a consumer without generation capability), or a community comprising a mix of prosumers and consumers. The market accommodates four types of transactions which are: transactions *between two individual prosumers*, transactions *between a prosumer and a consumer*, transactions *between two communities*, and transactions between *an individual prosumer and a community* (Montakhabi *et al* 2023). If one of the peers is a prosumer and the other is a pure consumer, then the transaction is one where the prosumer commits to share surplus electricity to meet the demand of the consumer. Consumers can be motivated by a heterogenous electricity product based on criteria such as renewable energy, price, localization, and reputation of the supplier (prosumer), among other factors. If both peers are prosumers or communities, then it is a transaction where surplus electricity is intended to meet the demand of the other prosumer or community. If one of the peers is an individual prosumer and the other peer is a community, then the prosumer can either sell or buy from the community (Montakhabi *et al* 2023). In theory, the prosumer can trade within the community to which the prosumer belongs or another community. This flexibility is supported in a hybrid P2P electricity market, which accommodates all these transaction types as shown in figure 3.

(b) Platform operators

Platform operators are new roles that emerge in the P2P energy trading market, and are the agents who run the platform to facilitate P2P transactions. This is an entrepreneurial role and the projects being run by developers (see table 1 for developers) are positioning themselves to execute the role of platform operators and monetizing trading for revenues and profits. Platform operators typically operate independently from the grid, holding no generation and consumption assets, and instead facilitate the trading of electricity. Their revenue models may include registration fees, transaction fees, or a profit margin on the total trading amount (Heo *et al* 2021, Schwidtal *et al* 2023). In some cases, platform operators can generate cash flows from arbitrage between the wholesale and local markets (Schwidtal *et al* 2023). The role, responsibilities, and functions of the platform operator vary on the type of market structure. In centralized and distributed systems, platform operators may also act as coordinators, managing interactions with grid operators, dispatch, and network constraints. In decentralized markets, platform operators serve as facilitators without centralized control. When the platform operator and coordinator are separate entities, the coordinator manages grid interactions and optimizes asset operations to maintain electricity supply at the grid edge, and the platform operator handles the trading infrastructure (Schwidtal *et al* 2023). In a decentralized market without a coordinator, platform operators take on these roles ensuring peer interactions are smooth and efficient.

(c) Retailers

The transformation of the grid with more DERs challenges the role of the retailer the most. Originally introduced in deregulated electricity markets as intermediaries to supply small consumers with electricity

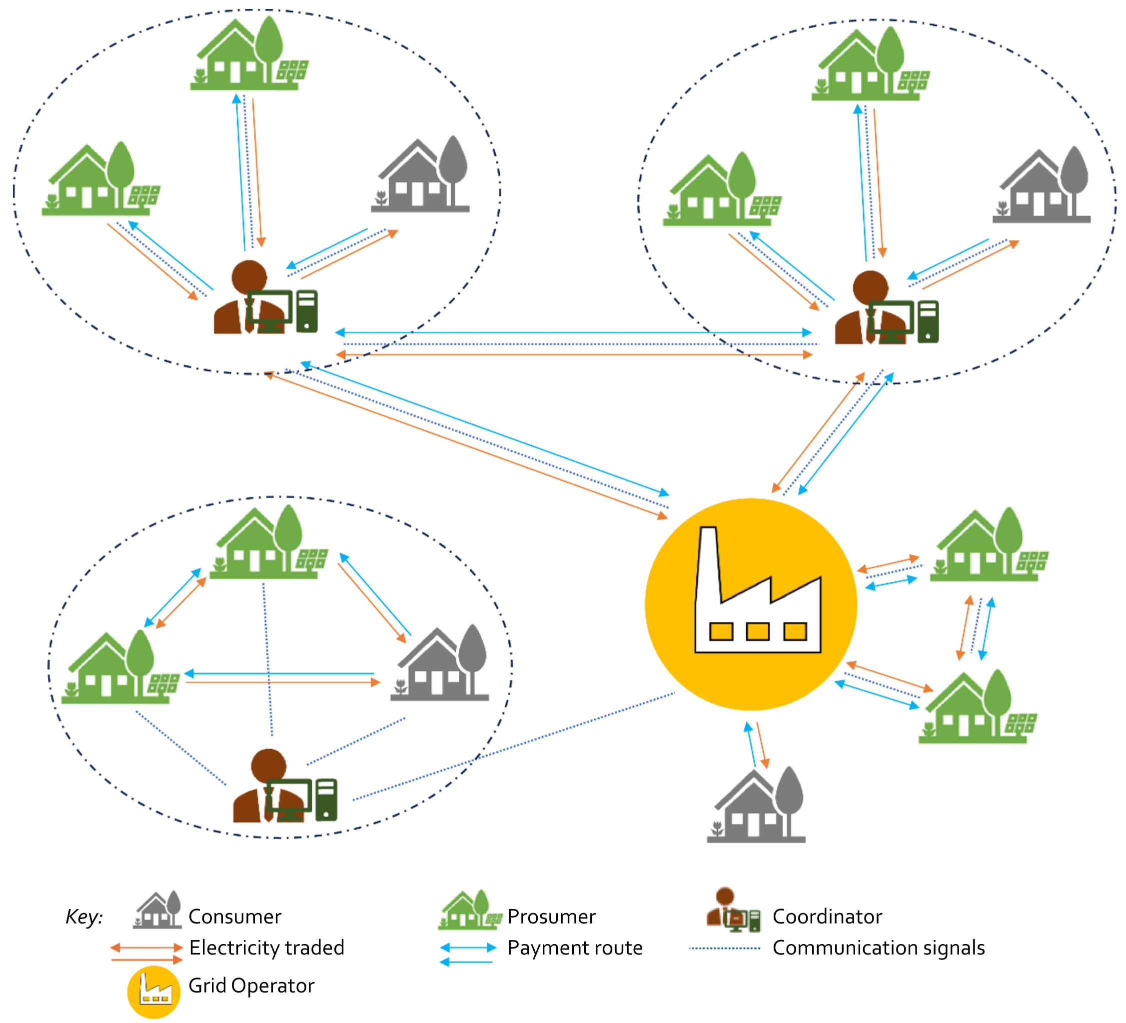

Figure 3. A hybrid P2P energy market showing interactions of a decentralized, centralized, and distributed market with the grid operator.

from the wholesale markets, the P2P trading market de-emphasizes the role of the retailer as a fundamental characteristic of a P2P trading market is that it does not need a retailer to facilitate trading. On the contrary, the lack of interference from the retailer enables enhance prosumer privacy and facilitates grid services (Tushar *et al* 2021a). However, retailers can still have roles within a P2P network. For example, they may provide prosumers electricity from the grid when their supply is insufficient to meet their demand. Tushar *et al* (2021a) suggest that retailers can operate in two potential roles: first, as a 'federated powerplant', where they can sell surplus generation from prosumers or energy communities to the spot or retail markets; or second, the retailer becomes the platform operator. In this scenario, the retailer absorbs the duties of the platform operator and acts as a middleman between P2P peers and the retail or spot markets. An example is the Brooklyn Microgrid in New York, which collaborates with local utilities to establish itself as a retailer within the P2P model (Mengelkamp *et al* 2018). In countries without a liberalized electricity market, the grid operator and the retailer can be the same entities, further blending roles within the P2P market.

3. Pricing mechanisms

Willingness to engage in trading is a key research area in the P2P energy trading literature and multiple studies have identified financial and monetary aspects as key motivators. In a survey in Germany, Löbbe *et al* (2020) revealed that cost considerations were the primary factor motivating participation in P2P energy trading. Similarly, Karami and Madlener (2022) found that cost savings and financial benefits play an essential role in German households' decision to purchase solar PV and partake in a P2P energy community. Hahnel *et al* (2020) showed that around 39% of German households—the largest group—are price-sensitive prosumers, demonstrating higher elasticity. Adewole *et al* (2023) observed comparable outcomes in a survey in Nigeria, where over 80% of Nigerians indicated an interest in energy trading for monetary gains, either to earn additional revenue or reduce energy expenses. Adewole *et al* (2023) found that economic incentives increased the likelihood of choosing a home with energy trading capabilities by 24%. In the Quartierstrom trials in Switzerland, 'most' households expressed a desire to sell their electricity at prices higher than grid feed-in rates, underscoring their expectation of higher returns (Ableitner *et al* 2020, Adams *et al* 2021).

A fundamental question in P2P energy transactions—and one essential to deriving economic benefits—is: how can prices be set to ensure fair and competitive trade that benefits all actors? To sustain P2P energy trading, economists and engineers have depended on economic theories to develop pricing mechanisms that are fair and competitive. Despite assumptions, economic theories provide a structured framework to understand human interactions and energy trade dynamics. Microeconomic theory, in particular, postulates that individuals within a market make decisions based on rational choice: they are assumed to have complete information and rational preferences, seeking to maximize utility through suitable pricing mechanisms. Economic theories emphasize an individualistic view of human nature, where each agent's actions toward utility maximization collectively explain societal function. Traditionally, a 'market' is defined as a setting (physical or virtual) where goods and services are exchanged, with prices and quantities determined by pricing mechanisms that ideally lead to an equilibrium where no peer is better or worse off. In contrast to centralized power systems—where the price depends on demand and supply, fuel prices, electricity supply costs, and local network costs, among others—P2P pricing mechanisms aim to create optimum outcomes that satisfy all participants within the energy trading community. When effective, these mechanisms can increase both the economic value of the trading community and the benefits to all actors involved, creating robust frameworks for P2P energy markets.

Four types of pricing mechanisms have been tested in real-world or experimental settings which are: constrained optimization, game theory, auction-based approaches, and deep reinforcement learning (RL). These mechanisms have distinct applications but are intended to provide an outcome that satisfies peers and other stakeholders within the P2P network. A comparative assessment of these pricing mechanisms is provided in table 4.

3.1. Constrained optimization algorithms

Optimization methods are used to solve quantitative problems to find optimal values of decision variables to an objective function that needs to be minimized or maximized, based on economic, environmental, technical, and financial constraints (Suthar *et al* 2023). For P2P energy trading, constrained optimization methods such as linear optimization (LP), non-LP (NLP), alternating directing method of multipliers (ADMM), and mixed integer linear programming (MILP) have been applied. Objective functions in P2P electricity trading often aim to maximize economic benefits and social welfare or minimize operational costs and energy losses. A generalized formulation of a P2P energy trade between a prosumer and consumer to minimize energy costs of consumers and maximize revenue for prosumers compared to exporting to the grid for all peers is as follows:

> Let m be the number of prosumers and n the number of consumers in a market with N_p and N_c as a set of prosumers and consumers respectively. Prosumer p_j trade in se_j units of surplus generation to the market and self-consume $\theta_{j,p}$ units of electricity. A prosumer $p_i \in N_p$ offers a unit trading price T_p to consumer $c_i \in N_c$ such that $P_{g,s} > T_p > P_{g,b}$ where $P_{g,s}$ is the grid selling price and $P_{g,b}$ is the feed-in tariff that the grid buys from the prosumer. To note that utility operators pay less for energy exported to the grid from prosumers (feed-in tariff is less than electricity consumption tariff). Prosumer $p_j \in N_p$ earns a revenue R by selling $\theta_{j,c}$ units of electricity to consumer $c_i \in N_c$ at price T_p to meet part of the demand d_i of the consumer. Per unit savings on energy costs to consumer $c_i \in N_c$ from buying from the prosumer instead of the grid is in the amount of π, such that $\pi = T_p - P_{g,s}$. Other variables and constraints that affect decisions with the P2P energy market are grouped under $\mathbf{x}$.
>
> Since $N_c = \{c_1, c_2, c_3, \ldots, c_n\}$ and $N_p = \{p_1, p_2, p_3, \ldots, p_m\}$, the total energy demand $D = \sum_{i=1}^{n} d_i$ demanded by consumers at time t and the total available surplus electricity available from prosumers in the P2P energy market $SE = \sum_{j=1}^{m} se_j$
>
> If $\theta_{i,j}$, $\theta_{i+1,j}$, $\theta_{i+2,j}$,…, $\theta_{i=m,j}$ are the units of electricity that prosumer $p_j \in N_p$ trades with consumer c_i at trading price T_{pj}, T_{pj+1}, T_{pj+2}, $T_{pj=m}$, the energy cost of consumer c_i, E_{cost} is given by equation (1) in the case $D = SE$ where prosumers surplus electricity meets consumers total

demand. This happens if a microgrid is operated under islanded mode,

$$E_{\mathrm{cost}} = \sum_{i=1}^{n} \theta_{i,j} \times T_{pi}. \tag{1}$$

In practical cases, $D > SE$ in the microgrid, the grid supplies the remaining electricity $\theta_{g,i}$ to meet the demand of the consumer such that the energy costs E_{cost} to the consumer $c_i \in N_c$ is given by equation (2). The objective function f of the consumer $c_i \in N_c$ seeking to minimize energy costs can be written as in equation (3):

$$E_{\mathrm{cost}} = \sum_{i=1}^{n} \left(\theta_{i,j} \times T_{pi}\right) + \left(\theta_{g,i} \times P_{g,s}\right) \tag{2}$$

$$f = \min\left(E_{\mathrm{cost}}\right). \tag{3}$$

Subject to $\sum_{i=1}^{n} \theta_{i,j} = d_i, \forall i = 1, 2, 3, \ldots, n$ and constraints $\mathbf{x}$.

The objective function g of a prosumer $p_j \in N_p$ to maximize revenue R can be written as in equation (4):

$$R = \sum_{j=1}^{m} \theta_{j,i} \times T_p$$

$$g = \max\left(R\right). \tag{4}$$

Subject to $\sum_{j=1}^{m} \theta_{j,i} = se_j, \forall j = 1, 2, 3, \ldots, m$ and constraints $\mathbf{x}$.

Optimization techniques are useful in modeling all parameters to project the workability of energy trading and have been applied in feasibility studies to test market designs or features of the P2P energy market. Each optimization type suits different P2P trading applications based on problem complexity, nature of relationships, types of variables, and constraints in the P2P energy trading model. Constraints $\boldsymbol{x}$ represent battery constraints, battery and grid power limits, pricing constraints, task duration constraints, PV technical properties, demand and supply side constraints, and inherent constraints of market designs, among other factors. LP is suitable to handle linear relationships for pricing and resource allocation. In this context, Lüth *et al* (2018) applied an LP technique to test two market designs with objective functions to minimize electricity costs in both designs—a *Flexi User* and a *Pool Hub* design. The Flexi User means that peers utilize their own BESS and Pool Hub means that peers utilize a community-owned BESS for trading. The study finds that both market designs result in a decrease in electricity costs, despite the Flexi User model incurring slightly more savings than the Pool Hub.

NLP handles non-linear relationships such as distribution and converter losses (varies quadratically) or power flow constraints. Iqbal *et al* (2021) tested a model that minimizes the overall converter and distribution losses in P2P energy DC network microgrids that reduces the losses by 25%. Other applications of NLP include Rodrigues *et al* (2020) and Long *et al* (2018) who tested different battery-related centralized market configurations to minimize community energy costs (see table A1 for a summary of relevant research). For more complex P2P energy systems, MILP is commonly used, allowing mixed variables, such as binary, continuous, and integer constraints. Relevant studies applying MILP include Nguyen *et al* (2018), Faia *et al* (2021), and Elkazaz *et al* (2021) who built P2P energy trading models with algorithms, incorporating binary digits for some variables. For example, Elkazaz *et al* (2021) represented power flows from and to the grid and the BESS by 0 and 1 digits. The authors presented a novel hierarchical and decentralized energy management system that optimizes energy consumption within households by shifting loads and maximize PV self-consumption.

ADMM works by decomposing an optimization problem into smaller problems that are comparatively easier to handle than the original problem. It is suitable for decentralized and distributed market designs and ensures the preservation of privacy by enabling computing of solutions locally (Paudel and Gooi 2019). For example, research has applied ADMM to maximize economic welfare for consumers and prosumers involved in the P2P energy market. The welfare function W_c of the consumer $c_i \in N_c$ can be given by $W_c = u_i$

Table 3. Types of game theoretic approaches.

Types of games	Definitions
Static non-cooperative	A non-cooperative P2P energy trading model where participants choose strategies simultaneously without prior knowledge of others' choices, making decisions only once.
Dynamic non-cooperative	A non-cooperative P2P model allowing participants to act at different times, with some observing others' actions before making their own decisions.
Canonical coalition	A cooperative P2P framework focusing on forming a grand coalition, distributing benefits equitably to ensure no participant has an incentive to leave.
Coalition formation	A cooperative process in P2P trading where participants group to maximize collective benefits while addressing individual incentives for stable collaboration.
Coalition graph	A cooperative P2P model using graph theory to represent connections and interactions among coalition members to optimize trade outcomes.

(θ_c)—$T_p \times \theta_c$ where $u_i\,(\theta_c)$ denotes the utility of the consumer when consuming θ_c units of electricity. For the prosumer, the welfare function W_p can be modeled by $W_p = u_j\,(\theta_p) + R$ where the revenue to the prosumer, $R = T_p \times \theta_c$. Maximizing welfare for consumers and prosumers can be given by functions h and w where $h = \max\,(W_c)$ and $w = \max\,(W_p)$. The ADMM formulation can be expressed as:

max $h(W_c) + w(W_p)$.
Subject to $A{\cdot}W_c + B{\cdot}W_p = C$
The augmented Lagrangian function can be defined as:
$L_p\,(W_c,\,W_p,\,z^T) = h(W_c) + w\,(W_p) + z^T\,(A{\cdot}W_c + B{\cdot}W_p—C) + \frac{\rho}{2}\,\|AW_c + BW_p - C\|_2^2$
where ρ is the penalty parameter. The iterative scheme of ADMM has three steps as follows:
$W_c{}^{i+1} \in \mathrm{argmin}_{W_c k}\,L_p\,(W_c,\,W_p^i,\,z^i)$
$W_p{}^{i+1} \in \mathrm{argmin}_{W_c q}\,L_p\,(W_c{}^{i+1},\,W_p,\,z^i)$
$z^{i+1} = z^i + \rho\,(A{\cdot}W_c{}^{i+1} + B{\cdot}W_p{}^{i+1}—C)$
where k and q denote the feasible region of W_p and W_c.
The convergence criteria of ADMM method is defined as:
$\|z^{i+1} - z^i\|_2 \leq \varepsilon$
where ε is a small positive number

Despite their utility, optimization techniques face limitations in capturing real-world P2P energy trading. Optimization models are deterministic models, assuming precise and accurate input parameters. However, real-world factors—such as diverse stakeholder priorities—introduce complexities that deterministic models may not fully address. While optimization models focus on quantifiable objectives like cost or efficiency, they do not always capture normative decision-making factors, such as ethical or social preferences or participants, which are integral to P2P energy trading (Carissimo and Korecki 2023). *In situ*ations requiring trade-offs and conflicting objectives, optimization methods may struggle to find a balance, underscoring the need for adaptable and context-sensitive models.

3.2. Game theoretic approaches

Game theory is an applied mathematical tool that analyzes decision-making and strategic behaviors for multiple peers involved in a competitive environment, such that the decision taken by one peer is influenced by other peers and will affect the actions of others (Tushar *et al* 2018a, 2018b, 2019, Paudel *et al*2019). The game incorporates the availability of information, behavioral logic, the rationality of players, types of strategy, and payoffs in a trade to choose optimal solutions. Unlike traditional optimization modeling, game theory accounts for the independence between peers, offering a nuanced approach to analyzing strategic interactions. Game theoretic approaches exist as non-cooperative (static, dynamic, or Stackelberg) games and cooperative games (Canonical coalition, coalition formation, and coalitional graph (Tushar *et al* 2018b). Table 3 defines the different types of game theoretical approaches.

In a non-cooperative game, players optimize their payoffs without interacting with each other either once, more than once, or at different times. This type of P2P energy trading seeks to achieve the Nash equilibrium solution—a state where no peer is better off by deviating from its action, provided all other peers are also taking their Nash equilibrium strategies (Tushar *et al* 2020a). Static non-cooperative games involve players opting for strategies simultaneously without knowing other players' choices. Dynamic non-cooperative game allows for sequential decisions where players can take actions at different times, allowing them to observe the actions of others. A Stackelberg game model hierarchical decision-making, with prosumers acting as leaders and proposing the price and quantity of electricity to be traded, and the consumers are followers who adjust their behavior in response to the prosumer's strategy (Jin *et al* 2020). In simple terms, a non-cooperative game G between a prosumer and a consumer can be written as:

$$G = \langle N, A, u\rangle$$

where N is the number of finite peers that is, the prosumer and consumer sets, A is the strategy profile for each prosumer and consumer and u is the utility or payoff of the game. Let $G' = (A, f)$ be a game between a prosumer $p_i \in N_p$ and a consumer $c_i \in N_c$ where $A \in A_{c,p}$ is the strategy profile set of a prosumer and consumer. The utility function is $f(u) = f_1(u), f_2(u), f_3(u), \ldots f_n(u)$ evaluated at $u \in A$. A prosumer can apply mixed finite strategies such as trading at different price T_p with varying revenue R. Their strategy set is $A_p = \{a_1, a_2, a_3, \ldots, a_n\}$. For consumer $c_i \in N_c$, the strategy set A_c has only two strategies which is to either accept or reject the offer of prosumer $p_i \in N_p$, and thus, the strategy set of a consumer is $A_c = \{\text{accept, reject}\}$. If a consumer chooses to accept the strategy of the prosumer to obtain utility u, consumer $c_i \in N_c$ expected utility function is given by $f(u)$ where $u = (a_1 \in A_p, \text{accept} \in A_c)$. The Nash equilibrium in this case is the condition where customer $c_i \in N_c$ accepted played strategy yields higher expected utility at $u = \text{accept}$ than when the expected payoff of the customer $c_i \in N_c$ chooses to reject ($u = \text{reject}$) the strategy. In mathematical form, the Nash equilibrium can be written as:

$$\forall_{i,j}, x_{\mathrm{i,j}} \in A\text{:}\ f_c\ (x_{\mathrm{i}}, \text{accept}) \geqslant f_c\ (x_i, \text{reject}).$$

Numerous studies (see table A2 in the Appendices) have applied game theory to demonstrate effective P2P energy trade using non-cooperative gaming and to determine if the Nash Equilibrium is achieved. For instance, Paudel *et al* (2019) showed that interactions among buyers and sellers through evolutionary and Stackelberg games converge to a stable state, reducing energy cost. Amin *et al* (2020) showed how motivational non-cooperative games can achieve lower electricity bills for consumers and increase revenue for producers. Bhatti and Broadwater (2019) incorporated fairness parameters in their mark*et al*gorithm to simulate energy trading among microgrids and retailers. A more realistic perspective on P2P transactions was provided by Jin *et al* (2020) tested a P2P trading algorithm based on a Stackelberg game and incorporated a distribution charge on prosumers in their algorithm, which is a fee to the utility company. Ali *et al* (2021) demonstrated a P2P energy trading system within a clustered microgrid consisting of solar, wind, and battery resources based on a multi-objective Nash equilibrium game theory and showed achievement of optimum payoffs.

Cooperative games emphasize collaboration by providing incentives for peers to form coalitions and achieve collective payoffs. The focus is on encouraging players to work together to achieve a common solution, such as through the Nash bargaining. Cooperative game theory ensures fairness in the allocation of benefits among peers, in contrast to the interaction-based focus of non-cooperative games. For instance, a typical cooperative game CG' is characterized by $CG' = (N_c \cup N_p, v)$ where v is the monetary benefit of the coalition of consumers and prosumers, an effective and sustainable coalition, can be met if: $v\ (N_c \cup N_p) \geqslant v\ (N_c) + v\ (N_p)$. A2 Studies on cooperative game theory focus on optimizing energy trading within P2P networks. Li *et al* (2020) and Tushar *et al* (2018a) propose mechanisms enhancing prosumer incentives and stable coalitions. Moniruzzaman *et al* (2023) incorporate coalition formation to reduce losses, ensure fairness, and maximize utility in local microgrids within a blockchain technology. Together, these studies highlight cooperative frameworks' potential to improve economic benefits, reduce system inefficiencies, and foster collaboration in energy trading systems.

Despite its effectiveness, game theory has some inherent limitations that affect its applicability to real-world P2P energy trading scenarios. First, game theoretic models assume perfectly rational peers who always aim to maximize their self-interest and utility, which may not align with actual human behavior. Second, these models require exact and complete knowledge and information which is rarely available in practice. Third, game theory overlooks psychological factors, emotions, and cognitive biases that influence decision-making. Fourth, many studies have been conducted in small, controlled environments or using lab-based prediction models, making it uncertain how scalable these approaches are for larger communities or complex strategies. Lastly, strategies in game theory are not malleable enough and may not consider

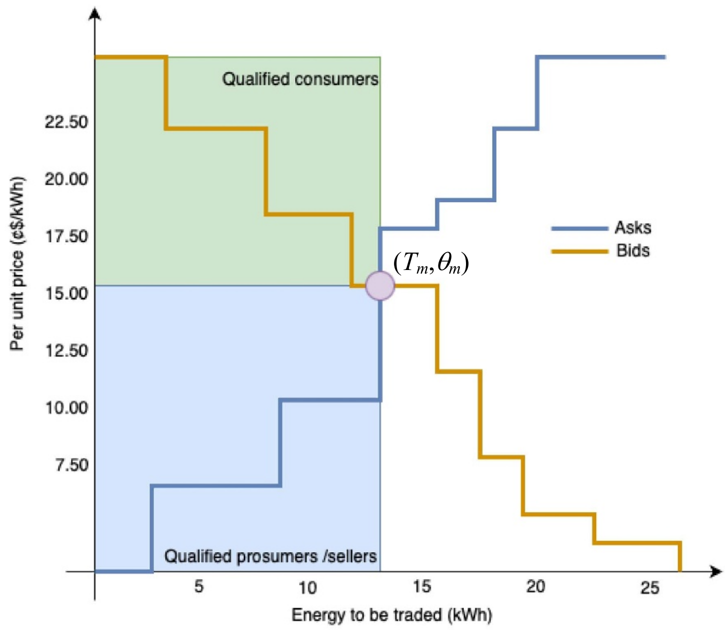

Figure 4. P2P market-clearing process through the double-auction.

unforeseen variables that can influence decision-making, and this limits their adaptability in dynamic and unpredictable settings.

3.3. Auction-based mechanism

Auction-based theory provides a robust framework for facilitating P2P energy trading. There are three types of auction-based mechanisms (reverse auction, forward auction, and double auction) of which the continuous double-auction method has been extensively applied in P2P energy trading networks (Muhsen *et al* 2022, Bukar *et al* 2023). A double auction market facilitates the exchange of goods and services among multiple buyers and sellers through a bidding process. In this type of market, interested buyers and sellers (consumers and prosumers) submit their bids and asking prices to an auctioneer (who can be the coordinator) within a given time. The auctioneer determines the market-clearing price from the Natural Ordering process where the consumer bids are arranged in descending order of price and prosumer offers are sorted in ascending order of their asking prices. This process generates a combined supply-demand curve that intersects at an equilibrium point, determining the quantity and price of the electricity to be traded (Malik *et al* 2023). Double auction markets are characterized by two properties: individual rationality and incentive compatibility. Individual rationality ensures that the trading price at equilibrium is at least equal to the seller's asking price and at most equal to the buyer's bidding price, guaranteeing that no peers in the auction are worse off. Incentive compatibility ensures that each peer can achieve optimal outcomes by acting according to their true preferences and values without resorting to strategic manipulation (Tushar *et al* 2020a, Malik *et al* 2023). A general formulation of the working principle of a double-auction approach is as follows:

> Consider consumer $c_i \in N_c$ in a given market with a set of consumer $N_c = \{c_1, c_2, c_3, \ldots, c_n\}$ and prosumer $p_j \in N_p$ in the market with a set of $N_p = \{p_1, p_2, p_3, \ldots, p_m\}$ prosumers. The bid to buy Q_b from consumer $c_i \in N_c$, submitted at time t for θ_i kWh of electricity at a price \$ T_b per kWh can be represented as $Q_{b,t}$ (c_i, t, T_b, θ_i). Similarly, the asking price Q_a submitted at time t by prosumer $p_j \in N_p$ to supply θ_j at trading price \$ T_p per kWh can be represented as $Q_{a,t}$ (p_j, t, T_p, θ_j). At closure of the bidding process, the auctioneer orders the bid prices T_b in descending order, and the asking prices T_p in ascending order as shown in figure 4. The intersection of the asking price and bidding price provides the market-clearing price T_m and the market clearing volume θ_m (Suthar *et al* 2023).

Recent advancements in P2P energy trading have leveraged innovative auction mechanisms to enhance market efficiency and social welfare, including game-theoretic principles to ensure fair and strategic decision-making (see table A3 in Appendices). Zhang *et al* (2018) developed 'Elecbay', a trading platform enabling interactions among prosumers, consumers, and distributed system operators in a low-voltage grid-connected microgrid. 'Elecbay' processes bids and orders from prosumers and consumers over 30 min intervals, ensures microgrid stability through network checks and facilitates electricity distribution via the grid. Combining auction-based market clearing principles with a non-cooperative game, the platform reduces energy exchange between microgrid and utility networks, maximizing microgrid-based consumption under competitive electricity prices. Chen *et al* (2019) expanded research by proposing a prediction-integration strategy optimization model for CDA-based P2P energy markets, integrating a market prediction model using Extreme Learning Machine to optimize prosumer operations and trading strategies. This method addresses CDA's stochastic nature by embedding predictive constraints, enabling simultaneous optimization of flexible resource scheduling and trading. Xu *et al* (2021) introduced an Iterative Uniform-Price Auction (IUPA) mechanism for P2P energy trading in a community microgrid, with a coordinator acting as the auctioneer. Their approach, designed to balance prosumer benefits and computational simplicity, encouraged greater engagement. Doan *et al* (2021) integrated game theory and auction principles within a blockchain to demonstrate real-time P2P energy trading, achieving equilibrium under different scenarios with thousands of peers engaged. Additional studies that further demonstrate the application of double auction frameworks are listed in table 6. Notably, US-based Brooklyn Microgrid employs an auction-based market-clearing approach.

The double auction mechanism is not without its limitations. One significant concern is the risk of collusion, where peers manipulate market outcomes—sellers might agree to maintain high prices, or buyers might suppress them. Detection and preventing collusion is challenging, leading to distorted prices and undermining market integrity. Market manipulation poses another risk for example, a dominant seller could withhold supply to inflate prices up, or a large buyer can reduce demand to drive prices down. Price volatility further complicates planning and budgeting for peers, creating inefficiencies and perceived unfairness in the market. Additionally, information asymmetry among peers results in an uneven playing field, where better-informed peers gain advantages at the expense of others, leading to suboptimal outcomes and eroding trust in the system.

3.4. RL

The integration of RL has recently attracted a lot of attention from the research community over the advantages the method holds over other approaches such as optimization and game theory. RL is a mathematical framework aiming to determine optimal trading actions to maximize a reward in an environment. As such, RL utilizes the influx of data collected from smart meters and agents' trading decisions to get 'trained' such that the model can perform automated actions on timescales of milliseconds. Unlike other computational approaches, RL focuses on learning through trial and error and inputs from 'agents' (peers) rather than modeling the environment and, thus RL is model-free and automated. Recent literature emphasizes the use of multi-agent RL, distributed trading models, and hybrid machine-learning techniques to create efficient and equitable trading ecosystems. The Partially Observable Markov Decision Process (POMDP) is the core framework in RL and consists of six main sets of parameters which are a set of states $\mathcal{S}$, a set of actions, a set of observations $\mathcal{O}$, a state transition operation $\mathcal{T}$and an immediate reward function $\mathcal{R}$ represented mathematically in a generic form as:

$$\mathcal{M} = \{\mathcal{S}, \mathcal{A}, \mathcal{O}, \mathcal{T}, \mathcal{R}\}$$

where $s \in \mathcal{S}$ represents the state of the environment, $a \in \mathcal{A}$ represents the action of agent $i \in I$ (consumers, prosumers, and other parties in the P2P trade), $o \in \mathcal{O}$ represents the agent's knowledge of the state, $\mathcal{T}(s' \mid s, a) = \Pr\{s^{t+1} = s' \mid s^t = s, a^t = a\}$ is the transition probability from one state to another given the selected action; and $\mathcal{R}$ is the reward of the agent which is a mapping from the Cartesian product of the state and action space to numerical values; $\mathcal{R}$: $\mathcal{S} \times \mathcal{A} \rightarrow \mathbb{R}$. Each agent i employs a policy conditioned on its private observation $\mu_i\ (a_i \mid o_i)$: $\mathcal{O}_i \times \mathcal{A}_i \rightarrow [0,1]$ to choose actions and execute the transition $\mathcal{T}$ to obtain immediate reward in time step t, $r_{i,t} \in \mathcal{R}$. The objective function of each agent i is learning a policy that maximizes the total expected return $R_i = E_{s\sim\mathcal{T},\ a_i\sim\mu_i,\ \ldots,\ a_I\sim\mu_I}[\sum_{t=0}^{T} \gamma^t r_{i,t}\,(s_t, a_{i,1}, \ldots, a_{I,t})]$ where $\gamma \in [0,1]$ represents the discount rate balancing the expected rate in the future and T is the time horizon. A general formulation for the P2P electricity trading mechanism for each agent i can be represented with observations $o_{i,t} = [t, P_{g,s}, T_p, P_{g,b}, d_i, se_i, \theta_c, \theta_p]$. The action vector $a_{i,j}$ of each agent i at time step t consists of $a_{i,t} = [a_{i1}, a_{i2,t}, \ldots, a_{iN,t}]$ where N is the total number of agents (prosumers m, consumers n and other agents) and $a_{i,t} = f\ (\theta_i, \theta_j, T_p, T_b)$ represents the energy and price decisions which is the basis of the action. Eventually, the reward function $r_{i,t}$ is the utility of the agent i received from taking action $a_{i,t}$: $r_{i,t}\ (a_{i,t}) = u_{i,t}$.

The application of RL and other derivative methods in P2P energy trading is relatively new. Studies include Qiu *et al* (2021) who applied a derivative learning method of RL—the parameter sharing multi-agent deep deterministic policy gradient (PS-MADDPG)—to model households' participation in electricity trading. Qiu *et al* (2021) model explored heterogeneous households with diverse demand-side portfolios such as shiftable loads, non-shiftable loads, energy storage, solar generation, appliances demand, and electric vehicles, among other demand sources within the household. The RL model 'learns' from households scheduling flexibilities faced with the diverse demand-side portfolios and accomplished lower daily energy costs and demand peak. Sanayha and Vateekul (2022) proposed a novel RL-based algorithm with the double-auction method, which is less time-consuming, less complex, can result in higher savings for households, and scalable. Chen *et al* (2022) investigate P2P energy trading in an interconnected residential, commercial, and industrial microgrid sharing electricity, heat, and natural gas through a POMDP method showing that microgrids can maximize local energy and minimize operational costs. A recent study by Wang *et al* (2023) applied the POMDP method to model heterogeneous households and their demand-side portfolios, supporting earlier findings of Qiu *et al* (2021) in terms of the viability of the algorithm to perform, yet showing the POMDP method might lead to better maximization that other RL frameworks. Other studies include Xu *et al* (2020), Pereira *et al* (2022), Zang and Kim (2021), and May and Huang (2023) which have been summarized in table A4 in the appendices. Table 4 summarizes the key differences between the different pricing mechanisms reviewed in this article.

RL as a method faces some limitations. First, the decentralized and dynamic nature of energy markets introduces high variability in supply, demand, and prices, making it challenging for RL models to converge to optimal prices. RL models struggle to adapt to these fluctuations without significant retraining or fine-tuning (Xu *et al* 2020, Qiu *et al* 2021). RL oftentimes requires extensive training data and computational resources, making it challenging for real-time large-scale applications (Pereira *et al* 2022). Ensuring fairness is equally difficult as RL prioritizes individual rewards over collective rewards.

4. Enabling technologies

P2P energy trading has emerged from advancements in several key technologies including the EI, IoT, Artificial Intelligence (AI), Blockchain and cybersecurity mechanisms, and Communication Networks.

4.1. EI 'The Backbone' and internet-of-things 'The Enabler'

The EI applies the principles of internet technology to energy systems, enabling the integration, management, and distribution of DRE resources. Building on the concept of smart grid, EI incorporates advanced digital technologies such as blockchain, the IoT, artificial intelligence, energy routers, and related devices to create a decentralized, intelligent, and user-centric energy network. EI is envisioned as a 'cyber-physical system' that harmonizes physical energy infrastructures with digital solutions to optimize energy efficiency, sustainability, and accessibility (Wang *et al* 2018, Hussain *et al* 2020). As the foundation backbone for DRE systems, EI provides the overarching infrastructure such as advanced communication, control, and energy distribution networks. IoT, in turn, acts as the enabler of EI by deploying sensors, smart meters, energy management controllers, and other devices to monitor and control energy flows. P2P energy trading leverages EI's decentralized architecture and IoT's data-driven capabilities for operation. Blockchain technology ensures secure and transparent transactions within the EI, while IoT devices automate trades based on real-time data inputs within the digital platform (Zhou *et al* 2016, Hussain *et al* 2020, Zafar and Ben Slama 2022, Mahmood *et al* 2024).

4.2. Artificial intelligence 'The Optimizer'

AI optimizes P2P energy trading by enabling precise forecasting, automation, and decision-making capabilities to improve market efficiency and energy utilization. AI-driven algorithms (as described in section 3) analyze real-time data from IoT devices to predict energy demand, supply, and market trends with high accuracy. This capability is particularly crucial, considering the inherent variability of solar energy, thus ensuring that energy allocation matches real-time needs (Naresh *et al* 2024). AI integration in P2P energy trading enhances features, such as dynamic pricing mechanisms, demand-side management, and automated energy storage scheduling, leading to improved stability of the microgrid and cost efficiency (Mahmood *et al* 2024). Advanced AI algorithms can also detect anomalies in energy trading patterns, preventing fraud and inefficiencies while fostering trust among peers (Boumaiza and Sanfilippo 2024). By combining predictive analytics with automation, AI allows prosumers to optimize their trading decisions, revenues, and the resilience and scalability of decentralized P2P energy markets.

Table 4. Comparison of the technical features of different pricing mechanisms for P2P energy trading.

Aspect	Optimization	Game theory	Auction-based methods	Reinforcement learning
Methodology	Utilizes mathematical models to find the most cost-effective pricing and allocation of energy.	Applies strategic decision-making frameworks where peers maximize their utility.	Employs bidding systems (e.g. double auctions) where buyers and sellers determine prices.	Uses iterative learning algorithms to adaptively optimize pricing based on market feedback.
Pricing Dynamics	Statis or semi-dynamic; often pre-determined and centrally optimized.	Strategic and dynamic; influenced by the interaction of peers' strategies.	Dynamic; prices emerge from competitive budding processes.	Fully dynamic; adapts to changing environments and market behaviors in real-time.
Market interaction	Minimal prosumer interaction; focuses on global efficiency.	High interaction: pricing emerges from competition and cooperation among peers.	High interaction: driven by market rules and real-time bids /offers.	Medium to high interaction; pricing adapts to prosumer behavior but may need convergence time.
Scalability	High scalability; limited by computational complexity of the optimization model.	Moderately scalable; complexity increases with more participants.	Scalable; dependent on the auction platform's capacity to handle bids and transactions.	Scalable using multi-agent setups but computationally intensive.
Fairness	May emphasize efficiency over fairness; equitable pricing depends on the optimization objective.	Fairness depends on the payoff structures and cooperative mechanisms.	Fair if auction rules are well-designed; risks of market manipulation if poorly regulated.	Potentially fair, as prices emerge adaptively based on contributions and demand patterns.
Transparency	Transparent if models are shared; prone to opacity in centralized systems.	Moderate; transparency depends on how strategies and utilities are shared or understood.	Highly transparent; auction rules and results are explicit.	Medium to low; models are data-driven, and decisions may lack interpretability.
Energy efficiency	High; focusses on minimizing costs and maximizing overall system efficiency.	Moderate; efficiency depends on the equilibrium achieved by strategies.	Moderate to high' depends on market liquidity and competitive dynamics.	High; learns to balance energy supply and demand effectively.
Complexity	High; requires detailed data and sophisticated modeling.	High; requires understanding of strategic behavior.	Moderate; complexity lies in rule design and real-time execution.	Very high; requires significant computational power.
Key Strength	Ensures global cost-efficiency and system-wide objectives.	Captures strategic behavior and interaction effects.	Facilitates market-driven price discovery and competition.	Adapts dynamically to changing market and environmental conditions.
Key Limitations	Requires accurate data and assumptions; less flexible to real-time changes.	May lead to suboptimal outcomes if peers act selfishly.	Prone to inefficiencies if market rules or peers' behavior lead to gaming.	Computationally expensive; requires large-scale data for effective training.

4.3. Blockchain: 'The Trust Builder'

Blockchain technology underpins P2P energy trading by providing a decentralized and transparent platform for secure and efficient energy exchanges. It eliminates the need for intermediaries by using distributed ledger systems to validate and record transactions immutably, ensuring trust among peers (Zhou *et al* 2020). Unlike traditional applications that rely on intermediaries, blockchain enables these operations to run with the same level of certainty without central oversight. Transactions between a prosumer and a consumer can be managed by a 'smart contract', which is a self-executable set of rules for energy transactions that are immutable within the system. This secure, tamper-proof environment for trustless interactions is crucial for encouraging participation in local energy markets and fostering greater adoption of DERs. Smart contracts automate transactions by enforcing pre-defined conditions, such as price agreements and delivery verification (Muhsen *et al* 2022). Blockchain has been proposed as a transformative force in the energy sector, with applications spanning metering and billing, security, cryptocurrencies, grid management, and electric mobility, among others (Andoni *et al* 2019, Thukral 2021). Real-world implementations include the development of trading platforms for P2P energy sharing, such as Power Ledger (see table 1 for examples). Its appeal lies in its secure handling of contracts, data, and financial transactions, and its core attributes—privacy, authenticity, and trust—make blockchain integral to P2P energy systems (Soto *et al* 2021, Suthar *et al* 2023).

4.4. Communication networks

Communication networks are essential for enabling P2P electricity trading by facilitating real-time data exchange and ensuring seamless interaction between DERs and trading platforms. High-speed communication technologies, such as 5 G, offer low-latency and high-bandwidth connectivity, supporting instant updates on energy supply, demand, and pricing (Adenekan *et al* 2024). IoT-enabled devices integrated within these networks monitor energy production and consumption in real time, ensuring accurate trade settlements (Nguyen *et al* 2024). Local networks such as Neighborhood Area Networks and Home Area Networks connect local energy assets to P2P platforms, while Wide Area Networks ensure scalability by connecting geographically dispersed participants (Abrahamsen *et al* 2021). Additionally, communication networks enhance the reliability of decentralized trading systems by supporting blockchain integration for secure transaction validation and the execution of smart contracts (Wang *et al* 2024). These features make P2P advancements make P2P energy trading efficient, transparent, and conducive to the growth of renewable energy and decentralized energy markets.

5. Challenges and future research directions

To investigate the key challenges and potential research directions to overcome these challenges related to P2P energy trading, a STEP analysis is applied. 'STEP' is an acronym that stands for Social, Technological (or Technical), Economic, and Political (including legal) aspects and is an analytical tool to identify and evaluate the impact of existing and future factors that most influence the development of P2P electricity trading business activities at a macro level. This section delves into the challenges and future research prospects facing P2P energy trading, thereby providing a balanced perspective on the merits and demerits of the concept.

5.1. Social aspects of P2P energy trading

P2P energy trading introduces profound social dynamics by decentralizing energy exchange. However, it faces challenges rooted in societal perceptions, trust, and community participation. As such:

- ***Skepticism and trust issues.*** Potential peers are unfamiliar with the concept, leading to skepticism about its reliability and fairness. Limited understanding of blockchain and digital trading platforms exacerbates mistrust and hinders social acceptance, as peers fear data breaches, potential exploitation, or fraudulent activities (Junlakarn *et al* 2022, Schneiders *et al* 2022).
- ***Reluctance to change.*** Behavioral resistance to transitioning from traditional centralized systems to decentralized models is another challenge. Consumers accustomed to conventional utility services may find the active role required in P2P energy systems burdensome (Bassey *et al* 2024).
- ***Inclusivity.*** Another challenge is inclusivity. Communities with limited digital literacy or inadequate access to smart technologies are often excluded from P2P energy networks. This is particularly alarming for the developing and least developed countries, which might be deprived of such novel technologies despite an interest in these countries (Amuzu-Sefordzi 2020, Adewole *et al* 2023). The adoption of these systems can also exacerbate inequalities if wealthier participants dominate the energy trading landscape, leaving economically disadvantaged peers unable to fully benefit (Junlakarn *et al* 2022).

To address these challenges, fostering trust through transparent mechanisms, community education, and equitable access is essential. Incorporating local values and cultural norms can enhance social cohesion and acceptance. Community-driven initiatives traditionally require significant effort to build awareness and foster collaboration among participants. Effective education campaigns and user-friendly platforms can mitigate these barriers by highlighting the economic and environmental benefits of P2P energy trading while simplifying participation (Bassey *et al* 2024).

5.2. Technological and technical aspects of P2P energy trading

Technological infrastructure is fundamental to the success of P2P energy trading, yet it faces critical challenges in scalability, interoperability, and security.

- ***Scalability.*** Scalability issues will arise when existing grid systems are pushed to accommodate the bidirectional flow of electricity, often leading to voltage instabilities. As the number of prosumers within the P2P energy network increases, the risk of voltage rise at various nodes also increases, leading to potential network losses. Uncheck injection of power from all prosumers will compromise the safety and security of the network. An injection limit can be imposed on prosumers, but this will likely discourage participation and cause prosumers to lose interest (Tushar *et al* 2021b).
- ***Interoperability.*** Interoperability among various platforms and technologies also poses a barrier. Current systems lack standardization, hindering communication between different software and hardware components. There is also insufficient deployment of smart metering infrastructure and communication systems, which are essential for real-time monitoring, accurate billing, and efficient energy matching.
- ***Security.*** Data privacy and cybersecurity issues are particularly salient as P2P energy trading also involves a multitude of real-time financial and energy transactions. The decentralized nature of P2P systems makes them vulnerable to data breaches and malicious attacks, which can disrupt trading operations and compromise user trust. Blockchain is presented as a platform that can provide the necessary security protections—yet blockchain has no blanket security guarantees (Nabben 2021).

As P2P energy trading is in the pre-commercialization stages, the technical aspects of P2P energy trading are an area of ongoing research. Researchers and engineers are consistently improving the technology in terms of enhancing the security of the network, network constraint, network scalability, inter- and intra-community trading, multi-level battery storage management and making P2P platforms more user-friendly and operable.

5.3. Economic and financial challenges to P2P energy trading

Economic challenges in P2P energy trading stem from the high costs associated with the installation and maintenance of necessary technologies, such as DERs, smart meters, and accessing the trading platform.

- ***Transaction costs.*** Trading platforms have different business models, for example, subscription-based, such as peers taking a subscription to get access to the platform, or transaction-based, where the trading platform developers take a percentage from the trades as fees (like Uber or Airbnb). These transaction costs can be prohibitive and erode potential gains for peers, reducing the economic appeal of P2P energy trading.
- ***Market liquidity.*** Many pilot projects and operational systems have a limited number of participants, restricting opportunities for efficient energy trading. This lack of liquidity undermines the financial viability of the system, as fewer transactions limit economies of scale (Mohandes *et al* 2023). P2P energy trading also depends on dynamic pricing mechanisms, as reviewed in earlier sections, which can introduce unpredictability in revenue streams for prosumers.
- ***Absence of standardized financial models.*** The lack of standardized financial models in P2P energy trading presents a significant obstacle to investment and participation. Financial models play a critical role in helping stakeholders, including prosumers, investors, and policymakers, evaluate the economic viability and risks associated with new systems. The initial capital required for installing P2P energy trading can be substantial, and without clear financial projections and support mechanisms, many potential participants may not find the investment appealing. Transaction costs (including blockchain operational expenses) can further reduce financial benefits, creating a perception that P2P energy trading is less economically advantageous than traditional grid systems (Tushar *et al* 2021b, Bassey *et al* 2024).

The pricing mechanisms address part of these issues by enabling more competitive and flexible energy pricing. Pricing mechanisms reflect the real-time demand and supply and can maximize the value of energy traded, making the system more attractive for both buyers and sellers. Financial incentives, such as tax credits for installing renewable energy systems or rebates for early adopters, can lower barriers to entry. Additionally, policies that ensure fair compensation for prosumers, such as minimum guaranteed prices for surplus energy, can provide a safety net, encouraging broader participation. Creating a supportive ecosystem with clear financial models and incentives would not only stabilize P2P markets but also attract investments that can fund infrastructure development and technological innovation. Standardized financial frameworks, combined with supportive pricing strategies and government incentives, are critical for transforming P2P trading into a mainstream energy solution.

5.4. Political and legal barriers to P2P energy trading

The political and legal landscape for P2P energy trading is fragmented and often misaligned with the technical and economic realities of this emerging model. Barriers include:

- ***Legal ambiguities over grid access and ownership.*** P2P energy trading relies on access to local distribution networks, but in many regions, utilities retain exclusive rights to these grids. This creates bottlenecks, as utilities may view P2P electricity trading as a threat to their business models and resist enabling access (Schneiders *et al* 2022, Bassey *et al* 2024). Ownership of private microgrids introduces questions about responsibility for maintenance, liability during outages, and costs for upgrades to accommodate two-way energy flows (Tushar *et al* 2020b).
- ***Consumer protection.*** The consumer-centric nature of P2P energy introduces vulnerabilities that traditional energy systems do not face. Issues such as price manipulation, service reliability, and fraud can undermine consumer trust in these systems. Without clear legal frameworks to address disputes between peers and other stakeholders, prosumers may face difficulties resolving conflicts (Tushar *et al* 2021b). In addition, some regulatory bodies have yet to establish standards for the transparency of transaction records, further exposing consumers to potential exploitation (Schneiders and Shipworth 2021, Schneiders *et al* 2022).
- ***Data privacy and cybersecurity.*** The reliance on digital platforms, blockchain, and IoT-enabled devices in P2P electricity trading necessitates robust cybersecurity measures and data privacy protections. Many legal systems do not have such specific provisions to govern the use of granular energy data, leaving room for misuse or breaches. Questions about data ownership and the extent of consent required for sharing energy transaction information remain unresolved (Schneiders and Shipworth 2021, Schneiders *et al* 2022, Mohandes *et al* 2023).

Overcoming legal and policy challenges requires regulatory sandbox environments and adaptive legal and governance structures. Regulatory sandboxes allow testing of innovative P2P models without traditional constraints (in Thailand for example, Junlakarn *et al* 2022). Adaptive legal frameworks should permit multi-supplier licensing and empower community energy networks. Robust data governance laws are critical for addressing privacy and cybersecurity concerns, and safeguarding consumer trust. Collaborative policymaking involving governments, utilities, platform providers, and consumer advocates can create equitable, secure, and flexible systems. These reforms will enable P2P energy trading to thrive while ensuring regulatory compliance, fairness, and sustainability, paving the way for broader adoption of decentralized energy solutions (Schneiders and Shipworth 2021, Junlakarn *et al* 2022, Schneiders *et al* 2022).

6. A call for a more human-centered approach

Pricing mechanisms in P2P energy trading, as discussed earlier, predominantly focus on creating economic value by maximizing profits or revenues for prosumers and consumers within the trading community. However, another segment of the literature—though not expansive—challenges this emphasis on the 'market realm.' Based on earlier works of economic anthropologist Stephen Gudeman, Singh *et al* (2017 2018,) introduced the two dialectically connected realms in the P2P energy trading paradigm: the market and the mutual realms. The market realm reflects utility-maximizing reasoning, influencing cost allocation methods as described earlier. In contrast, the 'mutual realm' represents the less visible aspects of the economy, shaped by social connections and heterogenous values. In practice, prosumers and consumers live not only by trading goods and services but also by forming social connections. Decision-making in P2P energy trading, therefore, extends beyond the force of competition and economic efficiency of trading to encompass diverse motivations revealed through research into the mutual realm. Although studies on the mutual realm are less prevalent, they highlight non-economic forces besides or beyond profit maximization that drive participation in P2P energy trading that merit further exploration.

A key design challenge in the P2P energy trading lies in developing business models that balance market incentives with the social and behavioral aspects dimensions of participation. Focusing solely on profit maximization, revenue generation, or lowering energy costs may not sufficiently motivate engagement. As Dukovska *et al* (2023) argue, this narrow perspective overlooks other essential drivers for establishing P2P energy trading communities. For instance, a trial in Western Australia has shown that participants consider the P2P model 'too market-driven and not community-oriented enough' with limited potential to support the community, especially the disadvantaged or the ability to trade with individuals of one's choice (Wilkinson *et al* 2020). Ethnographic studies further emphasize the importance of social dimensions in P2P energy trading. Singh *et al* (2017) (2018), examined energy exchanges in a village in India, revealing the interplay between social relations and the diversity of values that motivate participation. Singh *et al* (2017) found that prosumers preferred monetary returns for distant connections and in-kind exchanges for closer relationships, underlining that both financial and ideological reasons motivations. Similarly, research in Germany (Ecker *et al* 2017, 2018) identified autarky aspirations among prosumers, driven by various motives—personal values, individual opinions, habits, and social norms over financial gains—which sometimes deter participation in the energy community despite financial benefits. In the UK, Wilkins *et al* (2020) found that participants valued P2P energy trading for advancing social and ecological goals, fostering meaningful community interactions, and empowering local actors in the energy market. van der Schoor and Scholtens (2015) identified social cohesion as a main motivator for driving engagement in local energy communities. Pires Klein *et al* (2021) proposed a social value-based assessment framework, uncovering 33 social value themes associated linked to P2P energy trading. These findings underscore the influence of non-market factors on participation, beyond the purpose of maximizing profits.

Critics argue that the integration of these social and behavioral insights into pricing mechanisms and algorithms remains insufficient. Addressing this gap could foster more human-centric approaches to determining electricity prices and quantities, ensuring that P2P electricity trading frameworks align more closely with the diverse motivations of participants.

7. Conclusion

The article has highlighted the potential of P2P energy trading as a decentralized and democratized approach to energy production, distribution, and consumption. By enabling direct energy transactions between prosumers and consumers, P2P energy trading fosters economic, environmental, and social benefits, aligning with the global transition to sustainable energy systems. This synthesis has delved into the mechanisms, challenges, and opportunities of P2P energy trading, with a focus on market designs, pricing models, enabling technologies, and evolving roles of stakeholders.

Key insights from the review emphasize the diversity of market structures in P2P energy trading, each with distinct benefits and challenges. Centralized models offer efficiency and robust oversight but limit autonomy and pose privacy concerns. Decentralized models empower peers and ensure privacy but face issues with scalability and market inefficiency. Distributed models balance these trade-offs, combining autonomy with limited coordination to enhance system resilience. Pricing mechanisms, ranging from optimization algorithms to game theoretic and RL approaches, demonstrate the potential to achieve fair, cost-effective, and efficient energy transactions, though their practical scalability remains a challenge. Additionally, these pricing mechanisms suffer from a key challenge as being too market-driven rather than more human-centered—which is highlighted in this review. The integration of enabling technologies is critical for the success of P2P energy trading markets. These innovations enhance transparency, trust, and real-time adaptability while mitigating technical and operational barriers. However, the challenges of cybersecurity, data privacy, and interoperability must be addressed to realize the full potential of these technologies.

P2P energy trading has significant implications for policymakers, industry players, communities, and researchers. Policymakers must develop adaptive regulatory frameworks that promote equity, grid stability, and participation while addressing challenges like data privacy and cybersecurity. Incentives for community energy projects and the inclusion of underserved groups are essential to ensure widespread benefits. For industry players, the focus should be on creating scalable, interoperable, and user-friendly platforms that integrate seamlessly with existing grids. Collaboration with grid operators and measures to mitigate risks like price volatility and market manipulation are crucial for building trust. Communities and prosumers, as key actors in P2P markets, require education, financial incentives, and accessible platforms to participate effectively. Researchers must prioritize interdisciplinary studies, integrating technical, economic, social, and policy dimensions to address the complex challenges of P2P energy systems. Empowering communities and advancing research will make P2P trading a cornerstone of a sustainable, inclusive energy future.

Data availability statement

No new data were created or analysed in this study.

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Appendices

Table A1. Summary of key research applying optimization techniques.

References	Optimization method	Summary of objectives and findings
Lüth *et al* (2018)	LP	A market design with each peer owning a battery and peers sharing a common community-owned battery yield appreciable electricity bill reduction, though the individual peer-owning battery configuration has higher electricity bill reduction.
Long *et al* (2018)	NLP	Simulated a two-stage aggregated battery control to minimize energy costs and sensing and communication requirements in a P2P energy network. Up to 30% reduction in energy cost achieved compared to the conventional power-to-grid.
Rodrigues *et al* (2020)	NLP	Analyzes optimal battery sizing in P2P networks, comparing user-owned and Energy Service Provided-owned batteries. Finds user-owned designs maximize net present value, lowering costs while promoting flexibility and local energy autonomy.
Iqbal *et al* (2021)	NLP	Simulated a model aimed towards minimizing system losses within a P2P network, highlighting the significance of considering convertor and distribution losses and demonstrating improved efficiency in sustainable community energy sharing.
Nguyen *et al* (2018)	MILP	Feasibility study of a P2P electric network with 500 households to show scalability and quantified cost savings. Up to 28% savings can be achieved by prosumers by savings decreases with excessive energy trading as pushes market clearing price down.
Alam *et al* (2019)	MILP	Simulated a near-optimal algorithm ECO-Trade that produce an optimization result in less than a minute and solve unfair cost distribution issues by ensuring Pareto optimality. Simulation shows that savings reduces at a point as where there is excessive generation to match demand.
Faia *et al* (2021)	MILP	Feasibility study of a P2P energy trading showing cost savings for the community as a whole and individual community members in the microgrid. P2P transactions can save up to 25% in the overall costs for community members and up to 9% for each prosumer
Elkazaz *et al* (2021)	MILP	Simulated a decentralized energy management system for P2P trading which optimizes household consumption through load shifting of electric appliances and maximizes energy for self-consumption and trading. Their model can reduce reliance on large BESS and improve battery life.
Drabecki and Toczyłowski (2022)	MILP	Simulated a model that optimizes energy costs and environmental quality (social, ecological and sustainability criteria than just costs). Intended to showcase a model that meet the preference of peers who are motivated by factors other than economic benefits.
Moret and Pinson (2018)	ADMM	Simulated a centralized market structure using an ADMM optimization method. The study shows the importance of a community manager (coordinator) in directing energy dispatch among prosumers in the community as well as payments and revenues.
Paudel and Gooi (2019)	ADMM	Simulated a P2P electricity trading model with maximize social welfare and determine energy price with minimal exchange of information with prosumers and consumers. Simulation results show feasibility of P2P energy trading through this model.
Lyu *et al* (2021)	ADMM	Simulated a fully decentralized model with multiple dynamic components consisting of heating, air conditioning, ventilation, battery energy storage system and electric vehicles showing its feasibility and ability of the model to attach social welfare maximization.
Guo *et al* (2021)	ADMM	Simulated a fully decentralized novel market structure with conventional P2P energy trading and features to negotiate for the reserve electricity. Uncertainty in generation is incorporated, yielding a model that is economic, secure and fair.

Table A2. Summary of key research applying game theoretic approaches.

References	Methodology	Summary of objectives and findings
Paudel *et al* (2019)	Stackelberg games	Study proposes a dual-stage P2P energy trading models in microgrids using Stackelberg games where sellers are leaders and buyers are followers. Findings show price and competition among sellers and buyers dynamics yield Stackelberg equilibrium, showing the model is effective.
Jin *et al* (2020)	Stackelberg games	Develops a P2P energy trading model with enhanced trading efficiency, ensured grid stability, and introduced a Distribution System Usage Charge to balance prosumer benefits and utility company costs in Korea.
Anoh *et al* (2020)	Stackelberg games	Explores P2P energy trading concept in virtual microgrids with prosumers as leaders and consumers as followers. Results show Stackelberg Equilibrium achieved with reduction in the energy costs for consumers, improved utility of prosumers and environmental benefits.
Chen *et al* (2021)	Stackelberg games	Develops a stochastic leader-follower game equally capturing prosumers' risk behaviors, optimized load strategies and dynamic pricing and enhanced system efficiency, stability, and equitable utility distribution.
Negmetzhanov *et al* (2021)	Stackelberg games	Introduces bundled trading with active and reactive power in P2P markets. Findings highlight decentralized trading benefits, achieving Stackelberg equilibrium while addressing renewable energy integration and maximizing social welfare.
Bhatti and Broadwater (2019)	Static non-cooperative games	Feasibility study for a static non-cooperative game incorporating a Market Reputation Index for prosumers in the P2P market. Outcomes highlight fairness, Nash Equilibrium achievement, and improved reliability in local trading markets using extremum-seeking algorithms.
Cui and Xiao (2020)	Static non-cooperative	Designs a non-cooperative game-based P2P energy sharing management model for buildings, aiming to optimize community energy efficiency. Results demonstrate improved economic benefits, energy efficiency reduced grid reliance, and scalability of the proposed framework.
Amin *et al* (2020)	Dynamic non-cooperative	Develops a motivational game with a five-layered architecture for the P2P energy trading market. Findings show Nash Equilibrium ensuring energy demands are met at reduced consumer costs and increased prosumer profits for grids and islanded operations.
Ali *et al* (2021)	Dynamic non-cooperative	The paper proposes a game theoretic multi-objective optimization model for P2P energy trading in clustered microgrids, optimizing generation resource sizes and payoff values with Nash Equilibrium achieved. Findings reveal improved annual profits and reliability in clustered architectures.
Li *et al* (2020)	Canonical coalition	Testing of a cooperative game-based P2P trading model that optimizes prosumer incentives and computational efficiency by constructing a grand coalition of prosumers and consumers. Findings shows total cost savings guarantees such that no users leave the grand coalition for sub-coalitions.
Tushar *et al* (2018a)	Canonical coalition	Introduces social cooperation-driven P2P trading mechanisms using coalition games. Results demonstrates the feasibility of forming stable coalitions through mid-market pricing, achieving cost savings, stable revenue distribution, and aligning with motivational psychology models.
Tushar *et al* (2020a)	Coalition formation	Proposes coalition game formation cooperative game framework for P2P energy trading prioritizing prosumer benefits. Findings show stable coalitions achieve optimal social cooperation and prosumer-centric outcomes. Real-world case studies in Australia provides validation of P2P model.

(Continued.)

Table A2. (Continued.)

References	Methodology	Summary of objectives and findings
Mussadiq *et al* (2020)	Coalition formation	The paper aims to improve prosumer participation through motivational models. Simulation results demonstrate reduced energy expenses, lower carbon emissions, and enhanced earnings for prosumers, validating the proposed model's effectiveness.
Moniruzzaman *et al* (2023)	Coalition formation	The paper proposes a blockchain-integrated cooperative game theory model for P2P energy trading in smart grids, addressing security, transparency, and economic benefits. Simulation results demonstrate improved prosumer financial gains, reduced distribution losses, and enhanced system reliability.
Azim *et al* (2021)	Coalition graph games	Presents a P2P energy model integrating local voltage management in grid-connected networks. Results demonstrates effective energy cost reduction, stable coalition formation using the Myerson value rule, and improved grid voltage control, highlighting the model scalability.

Table A3. Summary of key research applying auction-based theory application in P2P energy network.

References	Summary of objectives and findings
Zhang *et al* (2018)	The paper develops 'Elecbay', a P2P energy trading platform for grid-connected microgrid using game theory and an auction system that receive bids from prosumers and consumers. The model enhances local generation-consumption balance, reduces utility grid dependency, and demonstrates greater benefits with diverse peer profiles.
Chen *et al* (2019)	Proposes a PSIO model for prosumers in continuous double auction P2P electricity markets. The model enhances transaction efficiency and prosumer profits through integrated data-driven market predictions and optimization.
Haggi and Sun (2021)	Authors proposed a Multi-Round Double Auction framework for P2P energy exchange, integrating locational pricing to optimize costs, improve transaction success, and enhance prosumer participation. Simulation results demonstrate reduced transaction costs and improved prosumer participation in P2P energy markets.
Xu *et al* (2021)	Develops an IUPA mechanism for P2P energy trading in community microgrids. The mechanism achieves fairer trading prices, enhance local energy transactions, and reduces community costs, validated through simulations and equilibrium analysis.
Doan *et al* (2021)	Develops a real-time P2P energy trading system using a blockchain-enabled double auction-based game-theoretic model to maximize social welfare while ensuring privacy and scalability. Key findings demonstrate the proposed approach's efficiency in achieving optimal energy allocation and seamless integration with blockchain for secure, real-time trading.
Zhang *et al* (2021)	The paper proposes a P2P energy trading model using iterative double auction and blockchain for microgrids. It achieves a 22.3% improvement in social welfare, ensuring optimal energy allocation, market equilibrium, and decentralized transaction security.
Bandara *et al* (2021)	The paper introduces a flocking-based decentralized double action for P2P energy trading in neighborhoods, ensuring local trade with anonymity and security. The approach demonstrates higher success rates and faster convergence compared to centralized and distributed double auctions.
Liaquat *et al* (2023)	Paper develops a day-ahead P2P energy trading platform based on continuous double auction, integrating trading losses and network utilization fees. It demonstrates increased social welfare (17.75% improvement) and evaluates network and forecasting impacts on trading outcomes.
Malik *et al* (2023)	The paper evaluates four doble auction mechanisms—Average, McAfee, Trade Reduction and Vickrey-Clarke-Groves—for P2P energy trading in microgrids. It finds Vickrey-Clarke-Groves mechanism optimal for energy trading efficiency and average mechanisms better for maximizing social welfare.
Sim *et al* (2024)	Proposes a two-stage double auction mechanism for P2P energy trading within microgrids and interconnected microgrids to address supply-demand imbalances. It ensures incentive compatibility, budget balance, fairness and amplifies social welfare and trading efficiency, demonstrating feasibility for real-world applications.

Table A4. Summary of key research applying RL.

References	Summary of objectives and findings
Xu *et al* (2020)	Investigates P2P energy trading among microgrids under uncertainties in renewable energy and power demand variability, aiming to optimize each microgrid's utility. Using a blockchain-integrated multi-agent deep deterministic policy gradient (MADDPG)-based algorithm, it reduces energy costs by up to 6.21% and ensured transaction data security.
Qiu *et al* (2021)	Introduces a multi-cluster deep reinforcement learning (MADRL) approach for scalable coordination in P2P energy trading. The paper demonstrates enhanced cost efficiency, peak demand reduction, and computational performance using household clustering and mid-market rate pricing mechanisms in community energy markets.
Zang and Kim (2021)	Develops a reinforcement learning-based algorithm for managing P2P energy trading in local markets using community energy storage (CES). The algorithm maximizes trading profits, surpassing battery wear-out costs, and shows enhanced efficiency and economic benefits.
Chen *et al* (2022)	Proposes a multi-agent deep reinforcement learning (MADRL) approach for optimizing P2P energy trading and energy conversion in interconnected multi-energy microgrids (MEMGs). Results show significant reductions in operational costs and CO2 emissions while enhancing flexibility through energy conversion and trading, demonstrating the potential of MEMGs for sustainable energy systems.
Sanayha and Vateekul (2022)	Proposed an RL-based multi-agent asynchronous advantage actor-centralized-critic with communication (MB-A3C3) for P2P energy trading in households with solar installations. Findings demonstrate a 17% reduction in community energy bills through enhanced internal trading, reduced grid dependence, and improved computational efficiency via clustering and forecasting techniques.
Pereira *et al* (2022)	Develops a methodology using twin delayed deep deterministic policy gradient (TD3) and deep deterministic policy gradient (DDPG) for optimizing P2P energy trading in local energy markers. Result show significant cost reductions, increased energy transactions, and enhanced community sustainability by leveraging multi-agent RL in smart grids.
Wang *et al* (2023)	The paper proposes a decentralized multi-agent deep RL framework for optimizing energy exchanges and load scheduling in residential P2P energy markets by applying the POMDP. Demonstrated 10% cost savings, increased trading efficiency, and improved fairness, leveraging decentralized policy training for privacy-preserving and practical implementation.
May and Huang (2023)	Proposes a two-level multi-agent RL (MARL) framework to optimize dynamic pricing in community-based energy markets. Results show significant reductions in community electricity costs and increased self-sufficiency, highlighting MARL's potential for incentivizing energy trading and improving grid sustainability in local communities.

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