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A Comprehensive Review on Peer-to-Peer Energy Trading: Market Structure, Operational Layers, Energy Cooperatives and Multi-energy Systems

Zeynep Tanis[1,2] | Ali Durusu[1,3] | Nihan Altintas[1]

[1]Department of Electrical Engineering, Yildiz Technical University, Istanbul, Türkiye | [2]Nurol Solar Energy Production Inc., Ankara, Türkiye | [3]Clean Energy Technologies Institute, Yildiz Technical University, Istanbul, Türkiye

Correspondence: Ali Durusu (adurusu@yildiz.edu.tr)

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ABSTRACT

The energy sector is experiencing a significant transformation due to the rising focus on renewable resources, smart grid technology advancements, energy management improvements, and operational efficiency. To successfully manage this transformation, all actors in the sector need to reassess their roles, develop innovative business models, and formulate effective strategies and policies. Peer-to-peer energy trading significantly contributes to this transformation by allowing individuals to trade energy with one another directly. While it offers advantages such as reducing peak demand, lowering backup needs, and minimizing network losses, its deployment in electricity grids increases the complexity of transactions at both virtual and physical layers. This paper provides an in-depth analysis of the latest advancements in peer-to-peer energy trading, highlighting its main features and the potential advantages for both the grid and prosumers. By organizing existing research, examining the market structure, and detailing common technical approaches, this paper offers a thorough overview of the future of peer-to-peer energy trading and the energy transition. This study highlights the necessity for stakeholders in the energy sector to embrace innovative strategies to adapt to the evolving market dynamics and achieve sustainable energy objectives.

1 | Introduction

1.1 | Background

Traditional power generation models' environmental and cost challenges are now evident. Sizeable centralized power plants emit significant amounts of greenhouse gases, contributing to environmental degradation and climate change. Additionally, electricity generation often occurs in large, centralized power plants near fuel sources or away from densely populated areas. This results in high transmission costs and poses challenges for the efficient utilization of energy resources [1]. Increasing natural disasters such as hurricanes, droughts, fires, and floods emphasize the urgent need to reduce carbon emissions [2]. In this context, governments and industries worldwide are looking for solutions for a more sustainable and climate-friendly future by reviewing energy production and consumption models [3].

Renewable energy sources are central to this transformation. However, integrating these resources into the grid presents

Abbreviations: AC, alternating current; ADMM, alternative directional multipliers method; CHP, combined heat and power; DC, direct current; DER, distributed energy resources; DLMP, distributed local marginal prices; DNO, distribution network operations; DNSP, distribution network system provider; EMS, energy management system; FiT, feed-in-tariff; ICT, information and communication technologies; IES, integrated energy system; LEM, local energy market; LP, linear programming; LV, low voltage; MES, multiple energy system; MILP, mixed integer linear programming; NLP, non-linear programming; P2G, peer-to-gas; P2H, peer-to-hydrogen; P2P, peer to peer; TOU, time-based usage.

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challenges. The intermittency and dispersion of renewable energy generation pose challenges for traditional energy trading models. Innovative solutions like peer-to-peer (P2P) energy trading and advanced grid infrastructure enhance the energy system's flexibility, efficiency, and environmental friendliness. In particular, the growing presence of distributed energy resources (DERs) such as rooftop solar, storage, and electric vehicles necessitates new market models that support local exchange and autonomous operation [4].

The P2P approach to energy trade offers several advantages. First, it encourages localized consumption, which lowers outage costs for customers and reduces transmission losses and grid congestion while enabling utility providers to offer effective ancillary services and improve grid resilience. Furthermore, it maximizes the exploitation of renewable energy sources and minimizes waste gasses produced on-site by optimizing the use of DERs. Last but not least, end users gain from lower energy supply and transportation costs, and income potential from locally selling extra energy, encouraging investments in renewable energy, and building a more robust and sustainable energy ecosystem.

Although P2P energy trading has significant potential in the energy sector, it faces several complexities and challenges. First of all, the fact that it operates without a centralized control mechanism creates difficulties in ensuring consumers' trust in such a system [5, 6]. Issues such as consumer data security and account verification processes are vital, and adequate security measures may be required to address these challenges. Moreover, the various user profiles within the P2P energy system can complicate decision-making processes and lead to potential conflicts of interest between users [4]. This requires careful management, especially of energy trading parameters and competitive market dynamics.

To address these concerns, recent academic studies have proposed solutions using blockchain-based trading platforms, smart contracts for automated settlement, and game-theoretic or AI-driven optimization for real-time pricing and matching [7–10]. Nevertheless, these approaches raise their own challenges in terms of scalability, cost-efficiency, and regulatory compatibility. Questions also remain regarding how grid infrastructure costs should be fairly allocated among participants, and how system operators can retain observability and control in such distributed environments [11, 12].

Moreover, it is essential to integrate P2P energy trading with intelligent algorithms and management systems to cope with the inherent network constraints in the power grid. A full P2P energy trading model can cause negative impacts on the power system, especially given the constraints experienced in energy balance and power flow [13]. Therefore, innovative technologies and risk management strategies must be adopted to maintain security and stability in the system. Finally, stakeholders may have different needs, making it challenging to provide grid services efficiently. In this case, solutions such as flexible pricing models and customized energy trading policies can be developed to suit the needs of each stakeholder and maximize grid welfare. Successfully implementing P2P energy systems requires a comprehensive strategy integrating technical, managerial, and regulatory perspectives [14].

At the same time, technological advances in P2P energy systems and the development of smart grid infrastructure have led to developments in integrated energy systems. Developing integrated energy systems has brought increasing attention to multi-energy systems (MES). This is due to the advantages of interconnecting electricity, heat, gas, and transportation sectors, which enhance technical, economic, and environmental performance [15]. Professional prosumers arise due to the expansion of DERs under MES [16]. Thus, P2P energy trading—where prosumers exchange energy directly—emerges as a viable and promising method for facilitating the transition above. Moreover, incorporating various energy carriers instead of depending only on electricity enhances system flexibility. The necessity of integrating various energy systems has been emphasized, and analysing such integrated energy systems (IES) requires novel techniques and instruments [17].

However, despite growing interest, real-world implementation of P2P in MES remains limited and underexplored. Open questions persist regarding interoperability between energy carriers, valuation methods across sectors, and joint optimization frameworks [18–20]. The growing trends in the energy transition emphasize the importance of studying sector interconnection within P2P markets. Research increasingly focuses on understanding how combining different energy carriers affects the structure of P2P markets and explores the potential benefits for households engaging in multi-energy trading. Expressly, the high demand for electricity and heat in residential buildings necessitates an examination of their interconnection effects in a multi-energy market context.

1.2 | Structure of Research Conducted Towards P2P Energy Trading

This paper examines five critical components of P2P energy trading based on the latest developments in both industry and academia. The structure of the review methodology and the thematic topics addressed in this study is shown in Figure 1.

1.3 | Current Research Landscape, Knowledge Gaps, and Contributions of This Review

In recent years, research in P2P energy trading has expanded rapidly, driven by the global transition toward decentralized, digitalized, and decarbonized energy systems. Key trends in the field include the integration of blockchain and smart contracts for automated and secure energy exchanges, development of community-based energy trading models, exploration of cooperative governance structures, application of game-theoretic and learning-based optimization strategies, and the emerging focus on MES where electricity interacts with heat, gas, and mobility networks.

These diverse research directions indicate the growing academic and practical interest in P2P systems as a means to enhance grid flexibility, local energy autonomy, and prosumer participation. Despite these advances, the complexity and novelty of P2P energy trading still require further exploration to ensure scalable, secure, and socially inclusive energy markets.

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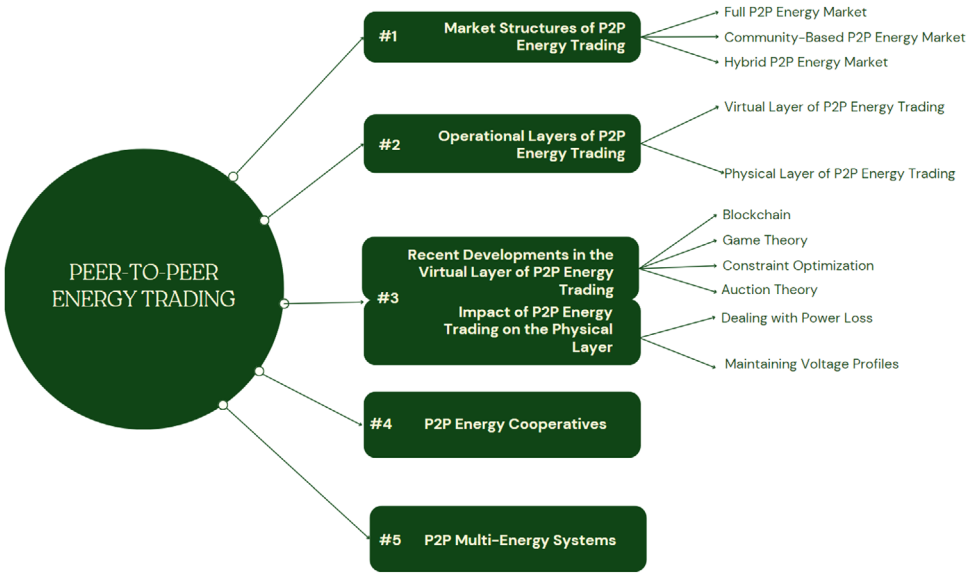


FIGURE 1 | The format of the study on P2P energy trading.

Understanding the state of advanced P2P research is crucial for several reasons:

1. To establish new research objectives in light of emerging technologies and market designs;
2. To address pressing challenges faced by modern energy systems;
3. To develop cost-effective and operationally viable trading mechanisms for real-world deployment;
4. To enable the design of new value-added services through peer-to-peer commerce.

Thus, a comprehensive understanding of the evolving P2P energy research landscape allows scholars and practitioners—particularly those focusing on distributed energy resources—to design creative and sustainable solutions aligned with future energy systems.

This review aims to contribute to the growing body of knowledge by synthesizing recent research that explores how P2P energy trading can transform energy markets and proposing a unified framework to guide future innovations.

1.3.1 | Overview of Existing Review Contributions

Several review studies have significantly shaped the understanding of P2P electricity trading. For example [21], provides a global overview of P2P energy initiatives, identifying key characteristics and challenges. However, its descriptive nature lacks a comparative evaluation framework, limiting its usefulness for model generalization. Framework-based analyses of P2P and community energy markets are presented in [22] and [23], detailing organizational structures, roles, and transaction mechanisms. While these offer structural clarity, they do not sufficiently incorporate physical layer constraints or address market coordination under real-world grid limitations.

Technological applications such as blockchain and distributed ledger technologies are explored in [7] and [24], which extensively discuss platform-level innovations. Yet, these works tend to assume ideal communication and consensus conditions, often overlooking scalability bottlenecks and privacy-preserving challenges in large-scale deployment. Optimization techniques and market-clearing algorithms are reviewed in [25], offering valuable algorithmic insights. However, this review lacks a critical comparison between centralized and decentralized optimization under regulatory and technical constraints. Similarly, [4] highlights game-theoretic approaches but emphasizes theoretical modelling without assessing the trade-offs between complexity and real-time applicability.

Structured discussions on methodology and future research priorities appear in [26, 27], and [28]. These works categorize research themes well but often analyse each methodological stream in isolation, e.g. game theory, optimization, and auction theory—without considering their integrative or hybrid potential in P2P environments. The integration of P2P systems in smart communities is detailed in [29–31], and [32], covering platforms, pilot projects, pricing, and implementation strategies. Although these studies offer rich implementation insights, most of them focus on electricity-only systems and overlook the growing importance of multi-vector integration (e.g. gas, heat, hydrogen) in real-world energy communities.

While these studies offer valuable insights, most analyse specific aspects of P2P systems in isolation. This review addresses this limitation by adopting a functionally categorized approach, examining five interrelated dimensions: market structures, operational layers, technical challenges in physical and virtual domains, cooperative models, and multi-energy integration.

1.3.2 | Research Gaps and This Review's Contributions

Despite the increasing academic interest in P2P energy trading, key research gaps persist. These include fragmented analyses,

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limited integration across technical and economic layers, and underrepresentation of cooperative and multi-energy perspectives. This review responds to these challenges as follows:

- **Gap 1: Fragmentation in P2P market structures**

  While the literature discusses full P2P, hybrid, and community models, there is a lack of unified evaluation regarding governance logic, coordination needs, and deployment challenges.
  This review contributes by: developing a structured taxonomy of P2P market models and comparing them across case studies and theoretical constructs.

- **Gap 2: Limited functional view of operational layers**

  Physical and virtual layers are typically separated conceptually, with insufficient focus on control hierarchies, energy-data interactions, and real-time system adaptation.
  This review contributes by: proposing a three-layer model (physical, virtual, adaptation) and illustrating interdependencies in P2P energy systems.

- **Gap 3: Separation of technical and economic modelling**

  Many models neglect the joint consideration of physical feasibility (e.g. grid constraints) and market mechanisms (e.g. pricing, optimization), limiting their real-world relevance.
  This review contributes by: presenting a framework that enhances both operational feasibility and market relevance through the examination of integrated modelling approaches that combine physical infrastructure constraints with economic decision-making processes.

- **Gap 4: Underexplored role of energy cooperatives**

  Although discussed in community contexts, the role of cooperatives in trust-building, inclusivity, and governance within P2P platforms remains insufficiently defined.
  This review contributes by: analysing cooperative models' potential to enhance fairness, decision-making, and stability in decentralized energy markets.

- **Gap 5: Immature understanding of multi-energy P2P systems**

  Most studies focus solely on electricity, neglecting cross-vector trading in heat, gas, and hydrogen.
  This review contributes by: synthesizing multi-energy P2P frameworks and proposing a research agenda for addressing interoperability, valuation, and coordination challenges.

By structuring the review around these gaps and contributions, the paper strengthens academic discourse and offers a comprehensive roadmap covering five interconnected domains: P2P market models, operational architecture, technical-economic alignment, cooperative governance, and multi-energy integration. The next sections delve deeper into these dimensions to support future research, policy-making, and system design.

1.4 | Paper Organization

The research is structured as follows: Section 1 offers comprehensive information on the objective, extent, and importance of the research. Section 2 thoroughly examines the many elements involved in P2P energy trading. Next, Section 3 introduces energy cooperatives and thoroughly examines the P2P market structure incorporating cooperative behaviour. Section 4 analyses multiple energy market scenarios within the framework of P2P. Ultimately, in Section 5, conclusions are derived. An overview of this structural flow is illustrated in Figure 2.

2 | P2P Energy Trading

"P2P" stands for "peer-to-peer", a distributed network design that eliminates the need for a central authority figure to mediate resource sharing between network nodes [33]. P2P, in the context of energy exchange, means decentralized sharing of local economies [34]. It is also characterized as a complete P2P market structure that allows prosumers to engage in flexible bilateral energy transactions outside the purview of the local market operator [35]. Therefore, prosumers:

- can fully control their energy resources,
- trade energy with each other simultaneously using reciprocal bidding processes;
- can operate as independent energy suppliers without being connected to a central energy provider [36].

2.1 | Advantages of P2P Energy Trading

From the perspective of the grid networks of electricity retailers and distribution network system providers (DNSPs), a P2P energy trading framework has the potential to deliver significant benefits to both prosumers and grid networks [26].

The benefits of P2P energy trading are summarised below:

a. **Flexible participation:** The prosumers are enticed to join the P2P trading platform because it allows them to express their preferences and pick the quantity of energy transferred in a competitive market. This is characterized by product differentiation and provides decentralized trade with product variety [37].

b. **Reducing electricity costs:** P2P energy trading enables families to become qualified users and participate in local energy markets (LEMs), which reduces the monthly cost of power. This is one of the most essential advantages of P2P energy trading [8]. Consumers have the opportunity to sell energy on P2P platforms at prices that are greater than feed-in tariff (FiT) rates but lower than time-based usage (ToU) tariffs, which results in financial rewards for both parties on the platform [38]. Although widespread

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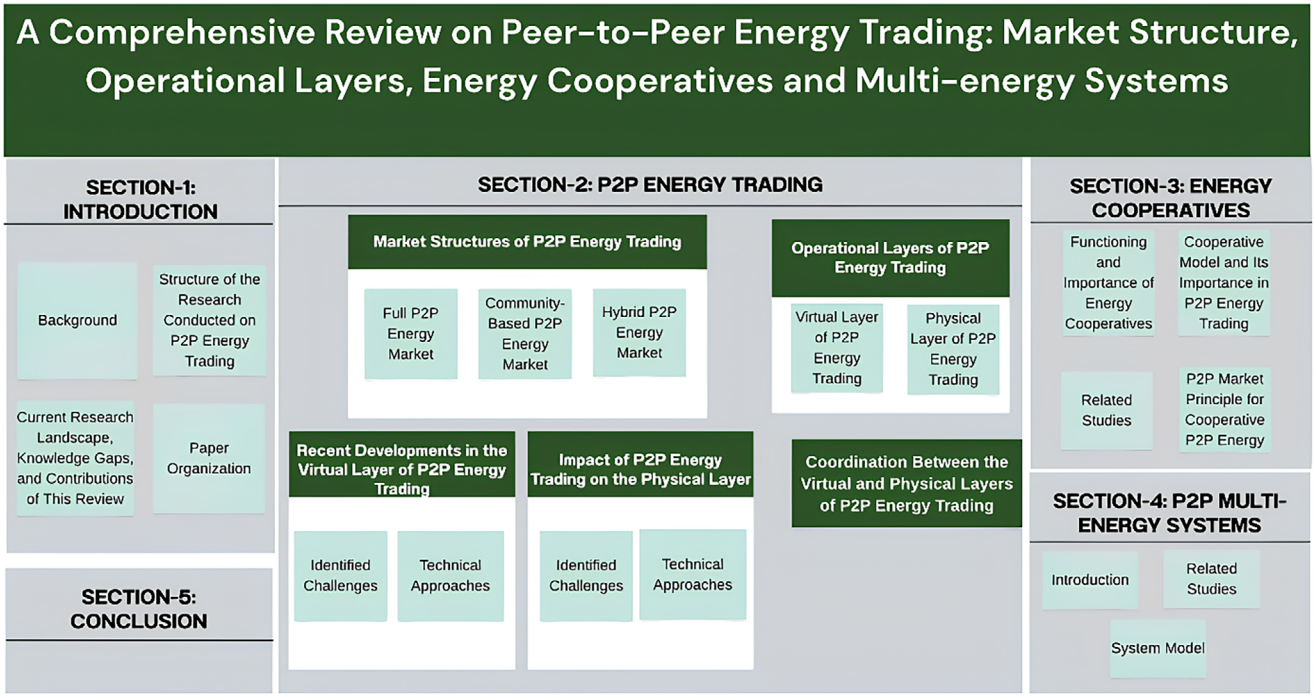


FIGURE 2 | The paper's organizational structure.

involvement in P2P energy trading is essential to lowering the cost of power [39], the amount of money saved might vary depending on the technique used by individual prosumers [14]. It has been suggested in the research that the amount of money saved by P2P sales and purchases may grow by anywhere from 4.36% to 12.61% [40]. Furthermore, the current body of research highlights the potential for producers to enhance their cost reductions by integrating energy storage devices into their decision-making process. For example, customers may enhance their savings by 28% in [41] and 30% in [42] by effectively maximizing the combination of photovoltaics systems and storage systems for P2P energy trading, respectively.

c. **Social connectivity:** The reciprocal trade enabled by P2P energy trading can deepen social relations within a community [8]. Moreover, through P2P systems, prosumers can donate surplus energy to their neighbours or social institutions to provide social benefits [6].

d. **Supply-demand balancing:** A community's energy balance can be achieved through active P2P trade, which also helps regulate sales and purchases [43]. This process facilitates consumers' efficient use of the energy they produce. Distributed ledger technologies, such as blockchain, track a community's energy production and consumption and propose transactions to prosumers to address energy balance [44]. This system also offers the possibility of rewarding P2P participants who contribute to the energy balance [45].

e. **Reducing peak loads:** P2P energy trading's ability to decrease the quantity of energy sent to end-users by power providers is a significant benefit, particularly during periods of high demand [11]. To lower energy use during high-demand periods, P2P members might work with centralized power suppliers [46]. During periods of high demand, P2P prosumers who handle variable loads might be awarded incentives [47]. Another strategy for lowering peak loads is re-regulating rates to enhance demand management [48].

2.2 | Market Structures of P2P Energy Trading

The traditional regulated electricity market operates from the top down, while P2P energy trading enables users to participate from the bottom up. Energy trading can be categorized into three primary types based on the level of consumer coordination: full P2P, hybrid P2P, and community-based P2P. Each structure offers consumers greater flexibility, diversity, and efficiency but has advantages and challenges. By enabling consumers to exchange energy directly, these structures offer a more innovative and participatory trading model beyond traditional electricity markets [22].

2.2.1 | Full P2P Energy Market

Without an intermediary, prosumers in fully decentralized P2P energy marketplaces handle all their financial transactions. Such systems give participants the freedom to trade energy and control the timing and conditions of their participation in P2P energy trading, offering great flexibility and scalability compared to community-based P2P markets [26]. However, the absence of centralized control can lead to efficiency problems and incomplete realization of social welfare. Specifically, when regulating the community's energy exchange, external parties, such as policy regulators and network operators, may encounter challenges [49]. The challenges of maintaining power system

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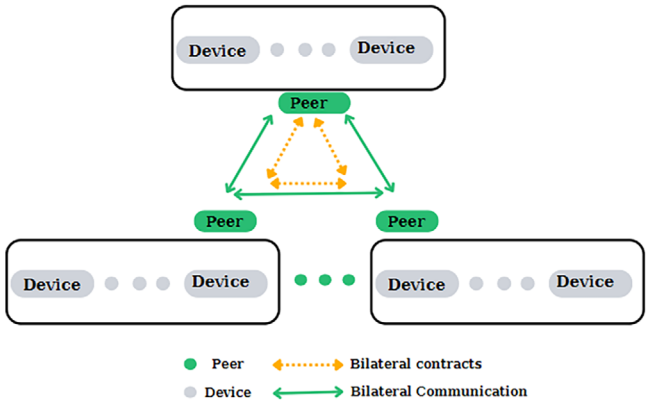


FIGURE 3 | Full P2P market design.

network constraints and grid reliability brought about by an entire P2P energy market may lead some network operators to restrict loads and remove users from the network, which may harm the functioning and reliability of the overall system. These problems make it hard to build full P2P energy trading [22]. A representative real-world implementation of a full P2P energy market is the Brooklyn microgrid (USA). This project enables prosumers in a New York neighbourhood to autonomously trade solar energy using blockchain-based smart contracts, operating without intermediaries. It demonstrates the potential of full P2P trading for localized autonomy and energy independence, while also revealing technical challenges such as scalability, grid balancing, and regulatory uncertainty. Figure 3 illustrates how prosumers share trade information in this market structure [50].

The study by [51] presents a bilateral contract network architecture that exemplifies full P2P trading without intermediaries, offering flexibility and autonomy. However, it does not sufficiently address technical risks such as grid congestion or voltage violations that may arise from completely decentralized control. Similarly, [52] and [53] focus on distributed mechanisms using smart contracts, but they tend to overlook scalability and interoperability challenges in heterogeneous prosumer environments.

A P2P energy-sharing framework integrated with electric vehicles and intelligent buildings is modelled in [54]. In [55], the authors propose a blockchain-powered P2P market platform. The hierarchical energy market structure is reshaped with energy management systems (EMSs) to be compatible with P2P trading [56]. A P2P market mechanism for inter-neighbourhood transactions is developed in [57], and an efficient model offering a fast market solution is presented in [58].

2.2.2 | Community-Based P2P Energy Market

A central coordinator is in charge of organizing user communications and trade choices in a centralized system. Following the trading procedure, the coordinator disburses the money to end users by pre-established guidelines. Participants in a community-based market do not exchange information or negotiate with one another on energy trade. Nonetheless, peers may influence the selection of trading parameters in energy trading by specifying the amount of energy they want to trade and the price at which

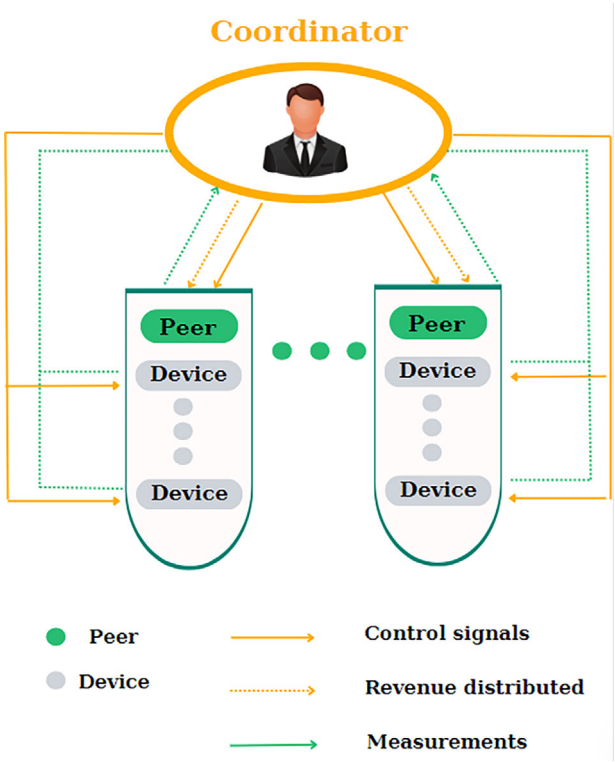


FIGURE 4 | Community-based P2P market design.

they want to trade. An essential advantage of a community-based market is its aim to improve the social well-being of its members. The structure and key interactions in this market configuration are illustrated in Figure 4. Furthermore, because users' DERs and flexible loads are directly under control, community-based market coordination may jeopardize end users' privacy [49]. One prominent example of a community-based P2P energy market is Power Ledger (Australia). Operating in residential settings such as apartment complexes and housing estates, Power Ledger enables residents to trade excess energy through a centralized platform that ensures trust, transparency, and fairness. While centralized coordination enhances operational stability, these systems also face challenges related to data privacy and user engagement [59].

In [60], consortium blockchain is used to ensure transactional integrity in community-based markets. While this approach enhances trust, it assumes a high level of user engagement and digital literacy, which may not be realistic in all demographic settings. Moreover [61], and [62] offer centralized scheduling and storage coordination schemes, but these models may risk undermining user autonomy and lead to privacy concerns due to centralized data handling. An iterative auction process establishes the market clearing price in the community-based P2P market model presented in [63].

Additionally, approaches to community-based P2P energy control that include many classes have also been published in the current body of research. For example, in [64], the authors demonstrate how to perform P2P trade reasonably between residential and business groups. The article [65] presents a system of P2P trading that takes into consideration the preferences of various

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community prosumers via its design. Lastly, in [66], prosumers who desire green energy are given priority in order to trade via bidding procedures within a P2P community encompassing several categories. A P2P market structure presents several significant obstacles, one of which is effective collaboration between prosumers and open-minded energy sharing [34]. These challenges emphasize the need for innovative solutions and cooperative strategies to enhance the functionality and adoption of P2P energy systems.

2.2.3 | Hybrid P2P Energy Market

The hybrid market is a hybrid combining the best features of both full P2P and community-based markets. For this reason, the market can be referred to as hybrid P2P. Compared to an entire P2P market, this one has more tightly controlled communication between traders and users, even while the energy trading systems are decentralized. In this market, end users conduct efficient transactions with each other through a coordinator. Unlike community-based markets, coordinators do not directly regulate how market players import or export energy. However, the coordinator might indirectly affect end users by choosing the proper pricing signals for P2P trading. As a result, end users in the hybrid market can retain more privacy while exchanging a limited amount of information [22].

Additionally, the hybrid market mechanism protects end users' freedom to choose how they want to trade energy. The development of P2P energy trading pricing systems that will deliver energy services to various local end customers is the primary emphasis of the research conducted on the hybrid market. Many end users will be encouraged to engage in energy trading by a fair price structure that provides pertinent incentives [49]. Figure 5 displays the framework for the hybrid market. An illustrative case of a hybrid P2P energy market is the Pebbles Project (Germany), developed by Siemens and the Fraunhofer Institute. It merges decentralized peer-to-peer transactions with centralized validation and coordination, achieving a balance between market autonomy and regulatory compliance. The project also showcases how hybrid models can be aligned with distribution system operators while supporting dynamic pricing and local optimization [67].

The hybrid P2P structure in [68] attempts to balance decentralized decision-making with centralized coordination. However, while this structure seems pragmatic, it still depends on predefined pricing signals and lacks dynamic adaptability to real-time network conditions. The aggregation-based design in [42] successfully improves system-level balancing but offers limited analysis on user-level economic fairness or incentive compatibility. Additionally, the model in [69] assesses efficiency, but its simulation assumptions are often idealized and lack real-world operational constraints (e.g. variability in DER outputs or communication delays).

Despite the diversity of proposed P2P market models, most studies focus on structural categorizations without embedding these structures into realistic network operation scenarios. There

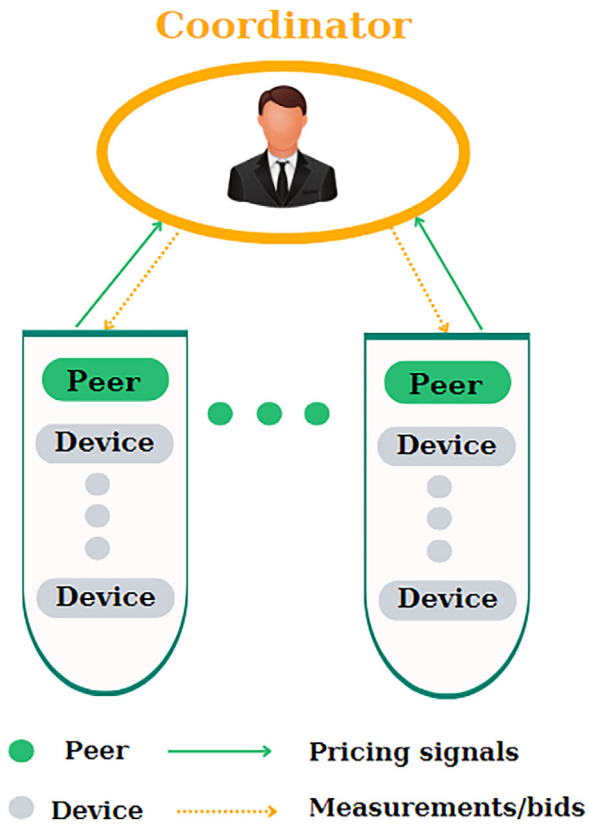


FIGURE 5 | Hybrid P2P market design.

remains a lack of comparative frameworks that evaluate models under shared criteria such as regulatory compliance, incentive fairness, and resilience to market volatility. This review contributes by bridging these dimensions within a unified comparative taxonomy. A structured comparison of different P2P market configurations, including their key features and main challenges, is summarized in Table 1.

2.3 | Operational Layers of P2P Energy Trading

This study also introduces novel dimensions by analysing the interaction between the virtual and physical layers, rather than treating them as isolated systems. In particular, feedback mechanisms are identified, such as how virtual layer demand forecasts influence physical load balancing operations. Furthermore, decision-making is recognized as a partially distributed process that extends into physical layer devices, including smart meters and inverters, where local logic supports system autonomy. The transactive meter is presented as a key interface between layers, handling both measurement and decision facilitation roles. Sociotechnical aspects such as user trust and transparency are also linked to the architecture of the virtual layer, which can shape user interaction with physical infrastructure. Finally, an additional conceptual layer—adaptation—is proposed to represent the system's dynamic response to external shocks and evolving user behaviour.

Unlike conventional classifications, this review not only distinguishes between the virtual and physical layers but also

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TABLE 1 | Outline of P2P market structures.

Market structure & references	Key features	Main challenges
Full P2P market [51–58]	• Independence; • Prosumer-centricity.	• Absence of central governance; • Stability issues.
Community-based P2P market [60–66]	• Shared interests; • Openness to collaboration and competition.	• Need for coordination; • Ensuring fair energy exchange.
Hybrid P2P market [42, 68–70]	• Customized structure.	• Inclusion of all stakeholders.

articulates the internal operational functions of each layer. This decomposition clarifies how digital coordination and physical infrastructure interact in real-world P2P energy systems.

While the classification of P2P energy trading into virtual and physical layers has been widely acknowledged in earlier literature [5, 26, 35, 71, 72], this review extends that model by functionally decomposing each layer. Specifically, we analyse the virtual layer through three interrelated functions—information sharing, local market configuration, and decentralized decision-making—while the physical layer is examined in terms of grid topology, data sensing, and integration with intelligent control systems. This layered functional model provides a more operationally detailed and systematic framework for evaluating and comparing P2P energy trading systems.

While the classification of P2P energy trading into physical and virtual layers is widely adopted in the literature, most studies offer a descriptive view with limited functional decomposition. For instance, [5] and [26] provide general frameworks for understanding the architecture but do not explicitly account for interdependencies between the layers or real-time adaptive control. The work in [71] highlights the use of blockchain for enabling coordination in the virtual layer, yet it largely omits socio-technical dimensions such as user trust, behavioural dynamics, and privacy—which are critical for real-world implementation.

Furthermore, studies such as [72] and [73] propose innovative blockchain and smart meter-based architectures for P2P energy trading. However, these rely on strong assumptions regarding communication infrastructure and system synchronization, which may not hold in practical settings, especially in developing regions or low-bandwidth environments.

To address these limitations, this review introduces an extended model comprising three operational layers: physical, virtual, and adaptation. The adaptation layer captures system dynamics, resilience mechanisms, and user behaviour responses, bridging the virtual and physical dimensions. This functionally decomposed framework enables a more comprehensive evaluation of P2P energy trading systems under realistic constraints and supports scalable and adaptive system design.

The functioning of P2P trading has two levels: the virtual layer and the physical layer [71]. Figure 6 is a visual representation of this.

2.3.1 | Virtual Layer

One of the components of the virtual layer is a protected platform that allows prosumers in the P2P network to access one another's energy-related information [5]. A secure communication platform transfers prosumers' energy excess, deficit, and price data. This data is sent from the transactive meter, a smart meter that differs from the typical energy meter to promote P2P trading [74]. These observations serve as the foundation for the creation of orders for the purchase and sale of energy. A productive P2P market mechanism has been developed in order to enable the purchase and sale of energy among prosumers. [26].

The essential elements of virtual P2P energy trading include an information-sharing platform, a local market configuration, and a decision-making mechanism to guarantee safe and efficient energy transactions. The information-sharing platform utilizes blockchain or distributed ledger technology for transparency and security. Local market setup promotes efficient energy trading and encourages using renewable energy sources. The decision-making methodology optimizes trading using algorithms and rules. When these components work together effectively, virtual P2P trading empowers consumers, offers income opportunities to producers, and enhances energy efficiency.

2.3.1.1 | The Platform for Sharing Information. P2P is a system that provides a secure and fast exchange of information that forms the basis of commerce [5]. The main objectives are to facilitate prosumers' communication with each other, provide equal opportunities, and ensure network security [71]. These platforms include various technologies such as Elecbay [75], consortium blockchain [60], Ethereum [72], and Hyperledger [73]. These systems aim to provide a fair and trusted environment for P2P energy trading.

2.3.1.2 | Establishment of a Local Market. In the P2P energy market, prosumers—individuals who produce and consume energy—play a crucial role. Some prosumers can adjust their energy consumption in response to various factors such as market prices, demand, and supply conditions. Additionally, a subset of these prosumers can purchase energy, allowing for greater flexibility and optimization within the market. This dynamic enables a more efficient and responsive energy system, where prosumers can actively participate in energy trading, balancing supply and demand and potentially reducing costs for all participants [22]. Supervised by a secure information system [5], this market includes detailed bid formats matching real-time sell

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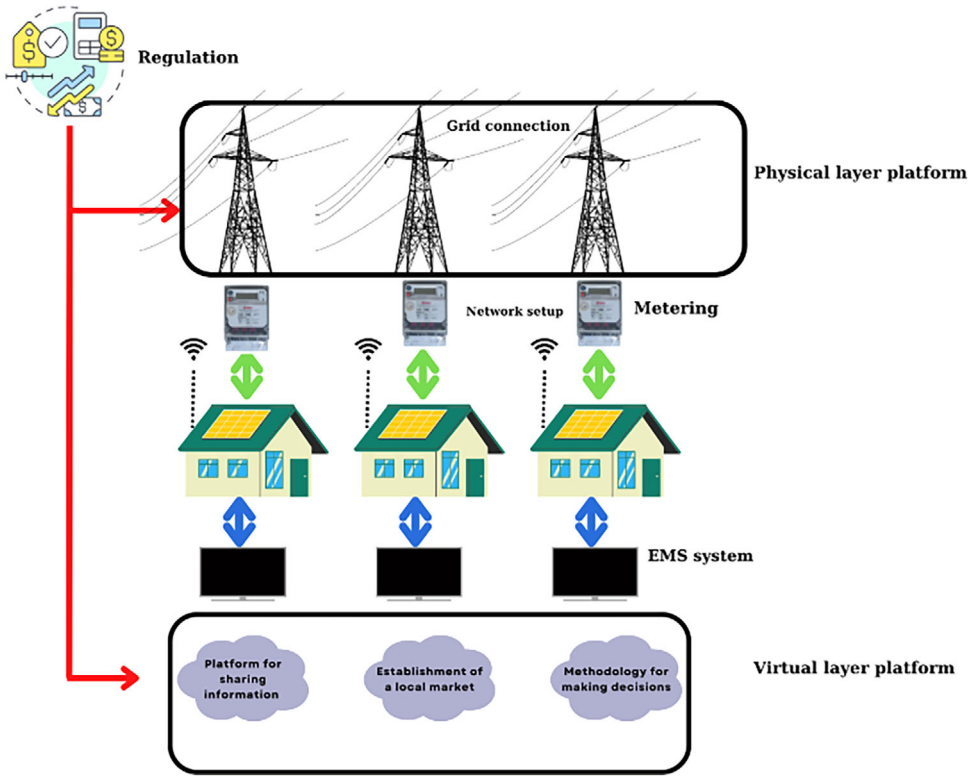


FIGURE 6 | A diagram showing the platforms for the physical and virtual layers of a P2P energy network.

and buy orders, payment rules facilitating trading, and standards enabling prosumers to adjust their energy allocations through EMSs [34]. If the energy price remains below a certain threshold, the EMS will acquire it from the P2P market. This strategy ensures cost-effectiveness and efficiency, allowing consumers to optimize their energy expenses by leveraging the most favourable market prices [71].

2.3.1.3 | Methodology for Making Decisions. One of the essential parts of P2P virtual layer operations, the decision-making mechanism performs several functions, including balancing local production and consumption, enhancing community benefits, evaluating and allocating the gains of so-called prosumers, and efficiently directing decentralized energy trade. These are essential duties for P2P marketplaces to operate well [5]. Understanding how different professional prosumers make decisions can be difficult. A practical P2P framework incorporates transparent trade agreements, equal welfare distribution for fair benefit sharing, and suitable market solutions to tackle issues and assure overall participant satisfaction, resulting in a harmonious and prosperous ecosystem. [39].

2.3.2 | Physical Layer

In this review, the physical layer is not limited to traditional infrastructure-based energy transmission but is examined as a multifunctional structure. This includes not only grid-level energy flow but also real-time data acquisition, power system monitoring, peer coordination, and integration with smart technologies such as blockchain-enabled automation.

Energy transmission occurs through the physical layer within a low-voltage (LV) distribution network [5]. The physical energy system comprises a distribution network operated and maintained by distribution network operators (DNOs) and a range of data-sensing and monitoring systems. These ensure real-time regulation of power flow and enable bilateral energy transactions among peers. In cases where microgrids are used, the physical layer also governs disconnection protocols and reconnection strategies in response to grid contingencies. Defining the grid connection point is crucial for maintaining balance between supply and demand. Measurement units located at the connection points monitor voltage, phase, and frequency data [6].

Beyond infrastructure, the physical layer incorporates advanced sensing from devices such as smart meters and solar inverters, which capture real-time data on energy generation and consumption. This data is transmitted to virtual trading platforms, enabling automated and efficient P2P energy transactions. Blockchain-based smart contracts facilitate trust, transparency, and security in energy exchange by recording and enforcing bilateral transactions without intermediaries.

The integration of digital data with physical infrastructure enhances the adaptability and intelligence of P2P systems. Apart from conventional electrical readings, sensors may collect meteorological data, load behaviour, and social signals to enrich system awareness and responsiveness [72]. In summary, the physical layer functions as the foundation of decentralized trading, connecting energy flow, data flow, and transaction execution into a unified operational space.

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2.3.3 | Interactions Between Layers

Beyond the functional decomposition of the virtual and physical layers, this section explores how these layers interact dynamically within P2P energy trading systems. The integration of information and control is not unidirectional; instead, bidirectional feedback loops are established to ensure synchronized system performance.

2.3.3.1 | Feedback Mechanisms. For example, demand forecasting algorithms in the virtual layer—driven by real-time data and user behaviour—can directly influence the dispatch strategies and voltage management protocols in the physical layer [76, 77]. Conversely, grid stability signals or congestion data from the physical layer can constrain virtual market activity by triggering curtailment or rebalancing measures.

2.3.3.2 | Distributed Decision-Making. Smart meters and local inverters are increasingly capable of executing decisions based on local environmental or pricing conditions. This implies that decision-making is partially embedded within physical infrastructure, a concept referred to as edge intelligence [45, 46]. Such distributed logic allows faster response and autonomy, especially in microgrid environments.

2.3.3.3 | Interface Devices. The transactive meter serves as a key interface, not only collecting energy use data but also executing pre-configured responses (e.g. automatic purchasing based on threshold pricing), blending measurement and control in one device [72, 74].

2.3.3.4 | Socio-Technical Feedback. User trust and perceived transparency of the system—facilitated through virtual platforms—directly affect adoption and responsiveness on the physical side. For instance, if algorithmic pricing models are perceived as opaque, users may reduce participation or override automated controls [7, 78].

2.3.3.5 | Adaptation Layer Proposal. To account for dynamic changes such as market volatility, weather disruptions, or social behaviour shifts, we propose an 'adaptation layer'. This layer comprises real-time control algorithms, forecasting models, and resilience strategies that span across both physical and virtual components. It serves as the system's intelligence layer, managing uncertainty and reconfiguration [9, 79].

2.4 | Recent Developments in the Virtual Layer

Recent advancements in virtual P2P trading have seen significant consolidation through the development of information-sharing platforms, decentralized market regulations, governance strategies, and the active encouragement of participation from professional prosumers. These initiatives collectively aim to foster a more transparent, efficient, and secure environment for P2P trading, marking a pivotal step forward in the evolution of digital marketplaces.

2.4.1 | Identified Challenges

Studies focus on effective pricing methods to increase prosumer participation in virtual P2P trading. This is coupled with the key objectives of securing decentralized transactions, reducing energy costs, and regulating the market [26]. The literature explores solutions to the challenges faced by this trading model.

2.4.1.1 | Designing the Pricing Mechanism. A practical pricing mechanism can increase prosumer participation in virtual P2P trading and encourage energy production. Innovative pricing mechanisms are essential for efficient P2P trading, and in this context, many studies focus on developing efficient P2P pricing strategies [39]. Among various methods, credit-based and multi-tier pricing schemes for frequent energy exchanges [73, 80], distributed pricing approaches to dynamically and optimally increase monetary gains [65, 81], and fair P2P pricing strategies to facilitate trade among multiple participants [64, 82] have been proposed. Policy-based pricing schemes have also been developed to support local energy trading [77, 83].

2.4.1.2 | Motivating Professional Consumers to Participate. Motivating professional consumers can enhance the sustainability of energy systems and provide economic benefits. The success of P2P trading depends on large-scale cooperation between prosumers and should be prosumer-driven [8, 39]. Several technical approaches have been proposed to reward prosumers, including contract theory [84, 85], game theory [6, 74], consensus-driven techniques [37, 52], auction theory [57, 86], collective control [42, 48], multi-category management [64, 80], reinforcement learning [9], agent-based modeling [69, 87], uncertainty management [88], and motivational psychology [8, 89]. These studies focus on developing strategies that support the P2P trading framework.

2.4.1.3 | Ensuring Reliability and Security. Ensuring reliability and security measures is crucial for the success of virtual P2P trading, with technologies like blockchain playing a significant role. The functioning of the P2P market takes place without centralized governance, which can lead to privacy concerns and issues with the platform's reliability [87]. P2P trading requires intensive interaction between prosumers, which can cause challenges such as communication and computational complexity, and the market performance could be better [90]. For P2P networks to operate effectively, resolving technological issues is essential. Research indicates that computational and communication complexities significantly impact transactions in P2P negotiation techniques. High computational complexity can negatively affect transaction speed and scalability, while communication complexity can lead to network congestion and increased latency [91]. Addressing these issues requires optimized algorithms, efficient communication protocols, and load-balancing strategies. By mitigating these complexities, P2P networks can become more efficient, reliable, and scalable. Hardware-induced computational and communication delays are caused by internet traffic or bandwidth limitations. Similar reliability issues have been investigated in the virtual layer platform [92].

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TABLE 2 | Overview of virtual P2P trading challenges and related studies.

Challenge	Research overview	References
Designing pricing mechanisms	• Developing fair and equitable pricing strategies to enhance financial benefits.	[39, 64, 65, 73, 77, 80–83]
Motivating prosumers to participate	• Using consumer-centric methods to encourage cost reduction in electricity.	[6, 8, 9, 37, 39, 42, 48, 52, 57, 64, 69, 74, 80, 84–89]
Ensuring reliability and security	• Addressing P2P communication complexities and securing financial transactions.	[87, 90–92]
Regulating the local market	• Structuring the P2P trading market for feasibility and sustainability.	[5, 11, 26]

2.4.1.4 | Regulation of the Local Market. Regulating the local market in P2P networks involves establishing uniform standards and protocols, implementing robust security measures, and creating mechanisms for dispute resolution. Ensuring transparency and accountability through audit trails and reputation systems, complying with local laws and regulations, and designing economic incentives and penalties are also crucial. These measures promote a trustworthy environment, enhance user confidence, and facilitate smoother, more reliable transactions in P2P networks. Regulating local markets can maintain fair and competitive energy prices, thus improving the effectiveness of virtual P2P trading. The success of P2P trading depends on government policies on energy and regulation [5]. Government responsibility in managing the architecture of the P2P market, determining taxes and subscription costs, and integrating various parties can lead to a more equitable, efficient, and stable market. However, governments must balance regulation with the need for innovation and flexibility, ensuring the market can grow and adapt to new technologies and changing consumer needs [11]. Governments can support P2P trading to incentivize the use of clean energy or limit its implementation until favourable conditions for the electricity market are established [26].

A consolidated overview of the major challenges in virtual P2P trading—pricing design, prosumer motivation, reliability and security, and local market regulation—and the corresponding literature is presented in Table 2.

2.4.2 | Technical Approaches

Integrating blockchain, game theory, constrained optimization, and double auction mechanisms is essential in developing advanced P2P trading platforms. These techniques enhance security, efficiency, fairness, and transparency, making communication and decision-making processes between participants more effective. This integrated approach ensures that P2P trading platforms are well-equipped to handle the complexities of modern energy markets and other trading scenarios.

2.4.2.1 | Blockchain. Blockchain was first introduced in P2P systems [93] and is managed as a decentralized data structure with well-defined consensus protocols [44]. This technology enables the exchange of information within P2P networks without a central authority [94]. Integrating blockchain effectively into P2P trading platforms or other applications requires a harmonious combination of automation, authentication, network infrastructure, data management, and communication protocols. Each technology plays a vital role in enhancing the blockchain system's functionality, security, and efficiency. By leveraging these technologies, organizations can build robust, scalable, and trustworthy blockchain solutions that meet the demands of modern digital ecosystems [95]. Blockchain-based P2P trading is formulated with smart contracts, which eliminate the need for intermediary services by codifying the terms of the contract [96]. Smart contracts are also effective for mitigating malicious activities [10].

Elecbay and similar platforms leverage blockchain technology to revolutionize energy trading. Through smart contracts, automation, and robust security, they offer a secure, transparent, and efficient P2P platform [97]. This modern solution benefits producers and consumers, reducing costs, increasing efficiency, and democratizing market access. It paves the way for a sustainable and decentralized energy future. Ethereum is an open-source blockchain platform that stores intelligent contracts built on its Ether cryptocurrency to program P2P information transfer [72]. Hyperledger is a public blockchain network part of the Linus Foundation and supports projects such as Sawtooth, Indy, and Fabric [73]. The consortium blockchain provides a cost-effective, shared distributed ledger and includes various certified nodes [60].

Ethereum has been utilized in various projects to enable secure energy trading within P2P networks [98]. A P2P energy system for a simulated power facility was constructed in [99] utilizing an analogous blockchain technology implementation. The hyperledger fabric framework, first introduced in [100], has been instrumental in developing a P2P energy model that facilitates a range of crowdsourcing and trading mechanisms. This platform was used in [78] to support binary trading functions and strategies.

The approach outlined in [101] and [102] ensures that privacy-oriented P2P energy trading and verification functions are developed on a solid foundation. This helps to create more reliable and user-friendly solutions in the field of energy trading. The consortium blockchain is used to facilitate secure multilateral P2P energy transactions between multiple prosumers. Furthermore, Optimal energy utilization, sustainability, and increased community utility and efficiency are the goals of the credit-based energy

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trading mechanism outlined in [73]. Modelling of double-layer incentive systems is studied in [103] on a consortium blockchain platform for P2P energy prosumers.

2.4.2.2 | Game Theory. Game theory is a mathematical model that analyses competitive situations in which the actions of individuals interact with each other. It is widely used in P2P energy trading to understand and resolve the conflicting interests of various participants [104]. Non-cooperative and cooperative games are the two primary categories of game theory, and they each look at players' strategic choices from various perspectives [8].

Non-cooperative games analyse participants' independent decisions that influence each other, and Nash equilibrium defines the mutually optimal strategies of such games [75]. The Stackelberg game models the strategic interaction between leaders and followers [45]. For P2P energy trading, these game theories have been used to understand energy exchange pricing and competition dynamics [76, 105]. Nash games have been used to incentivize prosumer participation [41] and to model energy networks [96], while Stackelberg games have been used to develop bidding strategies [106]. These methods have also been essential for optimizing costs and benefits and studying social behaviour in P2P energy trading [45, 107–109].

Cooperative games encourage participants to act together to maximize their collective income. There are three main types: canonical coalition games, coalition formation games, and coalition graph games [110]. The canonical coalition game maximizes the total revenue of coalition members [111], the coalition formation game examines possible coalition structures [74], and the coalition graph game analyses coalition interactions through graph theory [112]. Canonical coalition games facilitate long-term engagement in P2P energy trading, oversee the operation of many energy hubs with significant local involvement, ensure consumer alliances' stability, and incorporate climate and economic factors into energy trading models [113–115]. To ensure equitable revenue distribution, techniques including the Shapley value, weighted Shapley value, nucleolus, and mid-market ratio are employed [70, 114, 116]. A coalition-building game is a simulation game, usually focused on politics, business, or strategy. In the P2P community, this type of game usually involves a scenario in which players must work together in a virtual economy to form optimal coalitions, set trade prices, manage energy supply, and increase financial returns [46, 117, 118]. However, the use of the coalition graph game in P2P energy trading has yet to be developed in the literature.

2.4.2.3 | Constraint Optimization. Constrained optimization is optimizing an objective function under certain constraints [119]. This method is applied in P2P energy systems to increase efficiency by optimizing key factors. Researchers have applied various constrained optimization techniques for P2P energy trading, which has enabled the development of more efficient trading strategies and energy distribution methods. Several technical approaches are used in this field, namely linear programming (LP) and mixed integer linear programming (MILP). In P2P networks, LP is usually used for resource allocation and optimizing data transfer routes, while MILP allows for more complex decisions. MILP involves integer and continuous variables and can solve complex problems in P2P systems, such as efficiently managing resources and improving network performance. [119]. Nonlinear programming (NLP) solves optimization problems with nonlinear constraints and objective functions [119]. Alternating directional multipliers method (ADMM) is a technique that solves convex optimization problems by breaking them into smaller parts [120].

LP has been used to model efficient planning of P2P energy trade and decision-making strategies based on bilateral agreements [48, 85]. MILP has been applied in local generation, virtual bidding, and managing supply-consumption uncertainties to improve energy trading [77, 121, 122]. The MILP method has also been favoured for home-to-home and retailer-to-home energy transactions, designing energy management systems, and maintaining community-based P2P markets [56, 61, 123, 124]. NLP has been used to optimize energy sharing for two-stage control mechanisms and social welfare enhancement [125]. ADMM is proposed for P2P because it can manage complex issues such as energy producer and consumer preferences, communication security, energy network factors, and decision-making uncertainty. ADMM uses distributed optimization tasks to determine fair preferences, local computation to protect privacy, and dynamic network conditions to improve system efficiency. Stochastic optimization handles uncertainty and makes robust decisions [91, 126–128]. This method aims to provide an efficient and reliable energy distribution and trading process by providing solutions to various challenges faced in P2P energy trading.

2.4.2.4 | Auction Theory. Double auction, used in P2P networks, is a system where sellers set the market price by submitting bids. Sellers' bids are usually ranked from high to low, while buyers bid according to their maximum prices. In this process, buyers' and sellers' strategies and price expectations contribute to forming market dynamics so that the auction price reflects the market equilibrium. This method allows market participants to set prices competitively, creating a fair and efficient market [129]. Connecting production and consumption is the goal of a blockchain-based, double-auction P2P energy trading concept. The proposal's use of blockchain technology facilitates direct transactions between energy suppliers and consumers, prioritizing scalability, security, and transaction speed [60]. This approach has also been applied in [130] to model the pricing mechanism in a distributed manner. The best P2P energy pricing techniques for different kinds of homes were also determined using the double auction method [131, 132].

This technique has been used in [43, 53, 57, 75, 133–135] for P2P energy prosumers to increase their consumption, encourage participation in trading, reduce demand during peak hours, balance power, and direct auction transactions between global participants without intermediaries. Moreover, in [86], the iterative auction method is used to model P2P energy transactions for interconnected electricity grids. In this model, grid participants (households, businesses, small producers) submit their energy bids in iterative rounds, and this process continues until market equilibrium is reached. This approach makes energy trading more efficient and sustainable.

To summarize the methodological distinctions discussed across the three approaches above, it is important to emphasize that

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TABLE 3 | Methodological comparison of P2P approaches.

Method	Core focus	Application in P2P energy trading	Distinctive feature
Game theory	• Strategic behaviour among decentralized agents	• Prosumers' interaction, pricing, coalition formation	Models behavioural interdependence
Constrained optimization	• System-wide objective under hard constraints	• Load balancing, resource scheduling, cost minimization	Centralized, mathematical efficiency
Auction theory	• Market clearing via bidding and price competition	• Dynamic pricing, bid matching, double auction models	Price discovery through iterative competition

TABLE 4 | Methods used in the virtual layer.

Technical approach	The main focus of the technique	Applied methods	References
Blockchain	• Aims to develop non-centralized data structures that facilitate fast, secure, and dependable transactions in the P2P energy sector.	• Elecbay; • Ethereum; • Hyperledger; • Consortium blockchain.	[10, 44, 73, 75, 78, 94, 95, 97–103]
Game theory	• Seeks to analyse and strategize the competitive interactions between participants in P2P energy markets to ensure optimal and profitable outcomes.	• Non-cooperative • Cooperative • Nash game; • Stackelberg game; • Canonical coalition game; • Coalition formation game.	[45, 46, 51, 70, 75, 76, 105–109, 113–115, 118, 136]
Constrained optimization	• Focuses on refining P2P market goals under specific restrictions to streamline the efficiency of trading practices.	• LP; • MILP; • ADMM; • NLP.	[48, 56, 58, 61, 77, 85, 91, 121, 122, 124–128]
Auction theory	• Involves a systematic process where bids from multiple sellers and buyers are coordinated to establish market trade prices effectively.	• Double auction; • Iterative auction.	[43, 53, 57, 60, 86, 129–135]

while game theory, constrained optimization, and auction theory are often used in P2P energy markets, they serve distinct analytical and operational purposes. A comparative summary of the core focus, applications, and distinct features of each methodological approach is presented in Table 3.

Game theory models the strategic interactions among decentralized and autonomous agents. It is particularly suited for analysing behavioural decision-making in systems with interdependent actors, such as prosumer networks. For example, prosumers forming coalitions or adopting leader–follower strategies in energy exchange scenarios are modelled using cooperative or Stackelberg games.

Constrained optimization is typically used for centralized problem-solving where system-wide objectives are optimized under strict constraints. This approach is common in planning, scheduling, and cost minimization models. An example would be minimizing the total cost of energy use in a microgrid while satisfying demand and capacity constraints.

Auction theory enables dynamic price discovery and efficient market clearing through structured bidding and matching mechanisms. It is especially useful in distributed transactive platforms. For instance, in double auction systems, multiple prosumers submit bids at different price levels to match supply and demand dynamically.

These methodological frameworks are often complementary and can be integrated depending on the design goals of P2P systems. Table 4 provides an overview of the specific technical approaches applied in the virtual layer, along with their methodological focus, techniques used, and supporting references. Each method offers a distinct analytical perspective:

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- Constrained optimization emphasizes system-level efficiency.
- Auction theory addresses decentralized price formation and allocation.
- Game theory introduces strategic and behavioural interaction into market modeling.

Each method also presents limitations. Optimization models often require full system knowledge and centralized coordination. Auction mechanisms can oversimplify participant behaviour. Game-theoretic models, while rich in strategy, may be computationally intensive. Hence, choosing the appropriate method depends on the specific context and modelling objective.

2.5 | Impact of P2P Energy Trading on the Physical Layer

Current research is developing pricing strategies to create secure and transparent P2P energy trading platforms that integrate the decision-making processes of energy prosumers and encourage widespread participation. However, once the trading parameters are set at the virtual layer, the physical transfer of energy passes through the power system, which can create several constraints on the system. If this decision-making process considers the effects of P2P trading on the power system, energy transfers may stay within technical limits. For example, a virtually generated P2P trading strategy may only be approved at the physical layer by authorized DNSPs if it considers LV distribution network constraints [137]. The inherent features of distributed power grids, such as non-linearity, high R/X ratio, dispersed network topology, and imbalanced structure, are significant factors that affect the complexity and management of these networks. The lack of linearity can lead to unpredictable behaviours and stability issues, while a high R/X ratio may decrease the power factor and increase power losses. The dispersed network structure can result in communication and control challenges, and imbalanced structures can cause energy imbalances and power quality issues in specific areas. Therefore, advanced control systems and energy management strategies are required to manage distributed grids effectively [138].

Moreover, during the planning and construction of low-voltage distribution networks, failure to take direct user exchanges into account can result in networks encountering complexities. To avoid these complexities, DNSPs often impose strict rules on local power management [77]. Recent academic studies have identified two main barriers to physical P2P energy exchange specific to alternative current (AC) distribution networks: energy transport and voltage regulation challenges [139]. The literature states that the detailed dynamics of AC distribution networks cannot be adequately conveyed by direct current (DC) modeling and emphasizes the importance of AC power flow analysis to overcome these challenges [11].

2.5.1 | Coping With Power Losses

In physical grids, power loss occurs due to power flow, especially along feeder lines [140]. To maintain system reliability, upstream power suppliers must provide additional power over the total grid demand [46]. In P2P energy trading, early studies have traditionally assumed that power losses are negligible. However, given that power losses are unavoidable in practice grid lines, recent studies show these losses must be considered. Resistance and other losses that occur during energy transfer significantly impact energy efficiency and the economic feasibility of trading. Considering power losses helps develop more realistic and feasible trading models and ensures that trade pricing is fair and sustainable. Therefore, power losses must be comprehensively addressed in future research.

Some studies develop strategies to fairly distribute the losses incurred during P2P energy transactions and their costs among market participants. In P2P energy trading, fair allocation of losses is critical for the system's sustainability and the participants' satisfaction. The graph-based energy loss allocation system described in [141] is an innovative approach to achieve this fair allocation. This mechanism calculates the energy losses in the grid according to the transaction amount and location of the participants and determines the loss to each market participant accurately and fairly. Thus, the effects of unbalanced power flows are balanced, and each participant shares the costs in proportion to its contribution to the grid.

Meanwhile, proportional loss allocation for different entities participating in P2P energy trading and allocation of costs due to these losses are proposed in [72] and [142]. Matching processes such as P2P energy trading platforms are used in energy trading and distribution processes. In these processes, a transaction fee is usually applied to purchase and sell energy. These fees are intended to offset the costs of losses incurred during energy transmission, known as P2P energy losses. In particular, as mentioned in [143, 144], these transaction fees are used to recover the costs of energy losses in the system. The ADMM technique is used [14] to charge each participant to implement a loss cost allocation policy based on electrical distance. This approach is also adopted in [145]. Some other works aim to formulate strategic decisions to minimize P2P energy transaction losses and related costs using constraint optimizations. In [146], a routing framework that can minimize losses in a P2P energy network and provide optimal local distribution is designed with an ADMM approach. In [147], the objective of the penalty factor integrated into the P2P trading market is to improve market efficiency by reducing the energy loss between frequent financial transactions. This penalty mechanism acts as an incentive to reduce transaction frequency and minimize energy loss. In particular, it increases the costs of small and frequent transactions, thus favouring more significant and strategic transactions. Furthermore, the multilateral trading mechanism in [80] is intended to reduce the external costs associated with P2P energy loss.

Dynamic network structures were developed in [148] to minimize power losses in P2P energy trading. Furthermore, blockchain-based P2P energy trading schemes are reported to account for power loss [94]. Power loss analysis obtained by relaxing non-convex equality constraints forms the basis of a P2P energy market clearing mechanism [125]. A P2P energy market approach focused on power loss reduction in distribution networks is presented in [149], and a P2P energy market design based on electrical distance is presented in [150]. These studies aim to manage and minimize the energy losses in P2P energy trading.

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TABLE 5 | Methods used in the physical layer.

Technical approach	The main focus of the technique	References
Dealing with power loss	Incorporating power outages within the P2P trading framework and allocating the resulting expenses among professional consumers.	[14, 72, 80, 94, 125, 140–150]
Protecting voltage profiles	Improving voltage profiles and preventing overvoltage issues in the grid by implementing P2P trading.	[11, 151–157]

The study analyses the power losses during P2P energy transfers and aims to develop strategies and mechanisms to reduce these losses. In this context, technological, economic, and operational solutions are presented to improve the efficiency of energy trading and ensure the overall sustainability of the system.

2.5.2 | Preserving Voltage Profiles

Maintaining grid voltage profiles during P2P energy trading is critical to ensure safe and stable energy distribution. Deterioration of voltage profiles may cause damage to grid equipment and interruption of energy supply. Therefore, developing strategies for maintaining voltage profiles in P2P energy trading forms the basis for a sustainable and secure energy distribution system. This chapter addresses the technical and operational challenges of P2P energy trading and analyses various approaches to protect voltage profiles. The applications of P2P energy trading supported by local power generation in stabilizing voltage fluctuations are investigated in [151]. Preserving voltage profiles in P2P energy trading can be achieved by decomposing the grid, monitoring voltage levels, facilitating P2P trading, and employing decomposition algorithms to optimize energy flows while maintaining voltage stability. In [152], these algorithms dynamically adjust energy transactions, integrate feedback mechanisms for voltage deviations, undergo rigorous simulation testing, and are deployed with ongoing monitoring to ensure grid reliability and resilience. A fast ADMM technique is used in [153] to increase the convergence rate and offer another research on LV voltage control. When working on an optimization problem, this algorithm allows one to solve it by breaking it down into smaller parts, which usually increases the convergence rate. Therefore, using ADMM in a study on LV voltage management strategies can improve the speed and efficiency of the solution while maintaining voltage profiles in energy trading systems. This approach aims to address complex optimization problems more effectively to ensure voltage stability through energy trading. P2P energy trading is integrated with probabilistic and separable distributed local marginal prices (DLMPs) to avoid violations of LV limits in distribution networks. As mentioned in [77], these approaches are combined with P2P market design. In particular, the authors of the work in reference [11] reward professional consumers who help the DNSP maintain the voltage profile by using DLMPs.

However, significant P2P energy penetration can increase network voltages to such an extent that an overvoltage phenomenon can occur in some scenarios. In this context, some remedies have been described in recent studies. In [154], a P2P energy trading mechanism has been developed to analyse the effects of energy consumption fluctuations on voltage levels in LV distribution networks. This algorithm effectively predicts and manages voltage fluctuations in the distribution network by considering dynamically changing energy consumption patterns. Also, voltage spike-aware P2P energy trading methodologies have been developed in [155, 156] using the MILP technique, where centralized entities monitor power injection. This approach aims to optimize the energy flow in the network by analysing real-time voltage data through energy trading platforms. Thus, increasing the stability of the distribution network aims to ensure power quality and increase the efficiency of the users connected to the network. In order to control distribution network voltages, another method [157] has been proposed to reduce P2P energy penetration. This method aims to prevent excessive voltage fluctuations and increase the network's resilience by managing the integration of renewable energy sources into the network. A summary of the main technical approaches applied at the physical layer of P2P energy trading, along with their core objectives and supporting references, is presented in Table 5.

2.6 | Coordination Between the Virtual and Physical Layers of P2P Energy Trading

The virtual or physical layer has often been the focus of P2P energy trading research. Local market creation [5, 9, 22, 26, 56, 66, 71, 121, 127, 132], incentivizing the participation of professional prosumers in the P2P market [8, 37, 52, 65, 77, 89, 133], pricing and electricity cost reduction strategies [24, 40–42, 45, 49, 53, 57, 63, 64, 68, 70, 81, 82, 88, 107, 108, 114, 121, 136, 158–160], managing the supply-demand balance within the community [39, 43, 44, 62], developing communication platforms [55, 60, 73, 75, 78, 95, 98–102] and providing secure financial transactions [87, 90–92, 104]. Practical projects usually aim to test the virtual layer of P2P energy trading. When assessing the feasibility of the physical layer, the scalability of LV distribution networks may affect the virtual layer decisions of P2P energy prosumers. Therefore, the strategic P2P energy trading modeling developed in the virtual layer should be reorganized considering the realities of the physical layer.

3 | Energy Cooperatives

Increasing demand for energy and concerns over environmental sustainability have led to the search for new solutions in the energy sector. In this context, energy cooperatives are essential in bringing local communities together to sustain energy production and consumption. Changes in the energy sector, environmental issues, and the need to promote local energy independence led to the emergence of energy cooperatives. Until the mid-20th century, most energy cooperatives were established mainly in

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Europe. Today, energy cooperatives are widespread in many countries. They play a crucial role by promoting the use of renewable energy, increasing the participation of local communities in energy production, and making energy systems more democratic and transparent. Energy cooperatives are groups of local individuals, businesses, or communities that come together to contribute to energy production, distribution, or consumption. Usually, these cooperatives are democratically governed, and members participate equally in energy decisions. Cooperative members often work together to strengthen the local economy, reduce environmental impact, and meet their energy needs [161].

3.1 | Functioning and Importance of Energy Cooperatives

Energy cooperatives offer a decentralized, community-based model that allows members to invest in or consume renewable energy sources—especially local ones such as solar, wind, or hydropower. These cooperatives operate under democratic governance and are more responsive to community needs [162]. By collectively owning renewable energy systems, communities increase their energy independence, reduce transmission losses, and avoid price volatility associated with centralized energy markets. This localized control significantly strengthens local energy autonomy.

In addition to ownership, cooperatives empower members through coordinated decision-making in local energy planning and operation. By implementing microgrid-based configurations, they enable autonomous grid management capabilities, including black start support and islanding operations in emergencies. This ensures energy sovereignty and resilience against external grid disruptions.

Energy cooperatives also contribute to carbon footprint reduction through three key mechanisms: prioritization of clean energy portfolios, member education for low-carbon behaviour, and energy efficiency initiatives. Because cooperatives often establish policies that prohibit the purchase of fossil-based electricity, they effectively eliminate Scope 2 emissions at the community level [163, 164].

Moreover, cooperative frameworks often enable collective investments in net-zero infrastructure such as shared solar farms and community heat pumps. This bundling of resources accelerates decarbonization by leveraging economies of scale, while also enhancing inclusivity by allowing low-income households to participate in green energy adoption.

From a technical perspective, cooperatives enhance grid flexibility by managing distributed storage assets, implementing demand aggregation programs, and coordinating load through community-scale EMSs. These activities allow for real-time balancing, peak shaving, and voltage support [165, 166]. Cooperatives are increasingly acting as virtual power plants (VPPs), providing ancillary services to the distribution grid.

Furthermore, some advanced cooperatives integrate predictive analytics and AI-based load forecasting tools to preemptively manage local demand spikes. In multi-energy settings, they can co-optimize electric and thermal loads, increasing system-wide flexibility and minimizing operational stress on distribution networks.

In physical layer operations, cooperative-owned microgrids serve as localized balancing units. By leveraging joint control over smart inverters and storage assets, these communities help DNOs maintain voltage profiles and frequency stability, especially under high DER penetration.

3.2 | Cooperative Model and Its Significance in P2P Energy Trading

Cooperation in P2P energy trading allows participants to share energy, goods, or services. It is based on individuals or businesses with energy generation resources or energy storage systems sharing their energy with other participants [165]. Its main elements include resource sharing, mutual benefit, equity and fairness, sustainability, and community engagement, and technological progress [164]. Participants facilitate energy trade by sharing their resources, such as solar panels, wind turbines, or energy storage systems; cooperation connects those in need of energy with those who have excess energy, ensures fair and equitable resource distribution, and promotes energy independence and solidarity within the community.

Innovative technologies such as blockchain and smart contracts allow transactions to be secure and automated, helping sustainably develop this energy use model in local communities. These technologies facilitate transparent pricing, identity verification, and efficient settlement processes, which are essential in building trust within cooperative trading systems.

Beyond economic and environmental benefits, the cooperative model also offers technical system-wide advantages. Collective energy management practices—such as joint battery scheduling, aggregated demand response, and shared infrastructure planning—enable communities to operate more efficiently and adaptively. These capabilities contribute to greater grid resilience and operational stability, making cooperative-based P2P networks more robust in handling variability and uncertainty compared to individualistic energy models.

Furthermore, cooperative platforms also serve as shared digital infrastructure within the virtual layer. By standardizing data collection and sharing rules across members, cooperatives facilitate faster decision-making, more accurate demand forecasting, and transparent pricing mechanisms in decentralized energy markets.

The cooperative model also enhances grid responsiveness by synchronizing member actions in response to market signals or grid events. This ensures operational harmony and increases the ability to respond to supply-demand imbalances, contributing to both local reliability and system-wide flexibility. In contrast to non-cooperative P2P energy trading—where participants act independently and may lack coordination—cooperative-based systems enhance predictability and grid compatibility. By synchronizing peer actions based on community-defined operational rules, cooperatives also create conditions conducive to long-term investment in clean technologies and microgrid optimization.

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3.3 | Related Works

Existing literature generally focuses on market applications and distributed control in competitive gaming environments, where electricity prosumers are profit-driven and focused on maximizing their utility. In smart grids, bidirectional communication between prosumers and electricity suppliers is possible through advanced metering infrastructure [167]. Prosumers in a group, such as for-profit enterprises, can benefit more by joining together. Therefore, combining cooperative energy-sharing schemes and well-designed incentive mechanisms can drive broader adoption of sustainable energy practices, leading to more resilient and efficient energy networks.

In [168], an incentive system derived from the Nash bargaining theory was used to incentivize microgrids. Developing an energy trading framework based on the Nash bargaining model represents a significant advancement in managing microgrids within a distribution grid, promoting sustainable and cooperative energy practices [169].

To address the unpredictability of renewable energy supplies in a cooperative microgrid, the authors of [170] used a two-stage stochastic optimization approach. In [166], the authors discuss the energy management issue of a cooperative microgrid that incorporates renewable energy sources and storage facilities. The research aims to enhance the operation and coordination of microgrids to manage energy production, storage, and consumption effectively. Within this framework, methods for distributing resources and maintaining equilibrium between the availability and use of resources are formulated. The objective is to enhance the effectiveness and dependability of energy systems in collaborative microgrids.

In [171], the authors introduced a self-governing cooperative energy trading approach for professional customers. The objective was to enhance the efficiency and flexibility of the energy market by allowing professional consumers to engage in energy trading independently within a cooperative framework. These studies present various approaches to energy sharing and trading and demonstrate the potential advantages of cooperative energy sharing.

Recent studies have also explored how energy cooperatives manage multiple energy carriers—such as heat and electricity—in integrated systems. By coordinating solar PV, heat pumps, and thermal storage collectively, cooperatives offer a scalable structure for future multi-energy P2P networks.

3.4 | P2P Market Principle for Cooperative P2P Energy

In P2P energy markets, the absence of centralized service coordination often leads to competitive behaviours among participants, which can result in elevated transaction prices and reduced cooperation. Cooperative P2P models, however, offer an alternative paradigm where community benefit and stability take precedence over individual profit maximization. In such settings, members may not always gain immediate financial advantages, but they collectively benefit from reduced volatility, shared infrastructure, and improved energy equity [164, 172].

One key mechanism used in cooperative P2P systems is the forward contract, which enables participants to engage in predefined energy exchanges, reducing exposure to price volatility. These contracts help stabilize the market by accounting for potential mismatches between expected and realized generation or demand—particularly relevant in systems reliant on variable renewable energy sources [173]. Unlike speculative trading, cooperative forward contracts focus on long-term community value rather than short-term arbitrage.

In cases where participants face information asymmetry or behavioural uncertainty, cooperative P2P systems employ mutual risk-sharing strategies. These may include pooled reserves, shared maintenance contributions, or co-investment in backup storage systems. Such mechanisms enhance resilience and prevent the social fragmentation often observed in purely competitive energy markets [12, 174].

The strategic operation of cooperative P2P markets is frequently underpinned by cooperative game theory. Unlike non-cooperative games, which assume isolated rational actors, cooperative game models account for group behaviour and joint optimization. Canonical coalition games, for example, maximize collective welfare by allowing prosumers to pool their resources [114, 116], while coalition formation games focus on how such groupings evolve over time [74, 117]. More advanced models like coalition graph games integrate physical constraints (e.g. grid topology) into the strategic decision-making process, ensuring that collaboration is technically and economically viable [112].

This theoretical foundation translates into practical algorithms used for:

- Fair distribution of shared benefits,
- Stable coalition formation among heterogeneous prosumers,
- Efficient scheduling of demand response and storage assets,
- Network-aware energy dispatch within microgrids.

By embedding these cooperative principles into the market structure, such models support not only economic efficiency but also democratic participation, long-term trust, and social cohesion—making them highly suitable for local energy communities embracing P2P trade [114, 164, 172]. into the market structure, such models support not only economic efficiency but also democratic participation, long-term trust, and social cohesion—making them highly suitable for local energy communities embracing P2P trade.

4 | P2P Multi-Energy Systems

4.1 | Introduction

Traditional energy systems are undergoing a transformation toward heterogeneous structures that integrate energy production, transmission, consumption, and trading across multiple

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TABLE 6 | Real-world P2P multi-energy pilot projects.

Sector	Project & location	Description	P2P aspect
Heat	Royal Docks, London (UK)	Ectogrid system for 6,500 buildings sharing heating/cooling via low-temp smart grid	Bilateral heat exchange via smart contracts
	Framingham, MA (USA)	37 buildings share underground heating/cooling loop, coordinated by sensors and demand control	Peer-coordinated thermal balancing
	HYPERGRYD Horizon 2020	EU project using digital twins to optimize P2P heat trading in district heating systems	Predictive control for agent-level thermal trade
Gas/Hydrogen	E.ON Hanse, Falkenhagen (Germany)	2 MW P2G unit converting solar power to hydrogen, injected into local gas grid	Smart contract-based hydrogen matching among peers
	Thüga Group, Frankfurt (Germany)	360 kW electrolyser producing hydrogen for decentralized peer-level injection	Prosumer-driven balancing of gas assets
Transport	Toyota + Tokyo University (Japan)	EV-to-EV and EV-to-building energy sharing through bidirectional chargers	V2V and V2B P2P trading platform (TRENDE)
	NDRC Pilot, 9 Cities (China)	EVs act as peer traders for localized energy balancing within smart communities	Local P2P energy sharing via mobile EV storage units
	Oakland Unified School District (USA)	74 electric school buses using V2G to inject energy into grid during peak demand	Independent P2P dispatch algorithm for each vehicle

vectors such as electricity, heat, gas, and transportation [175]. This evolution is driven by the dual forces of the energy transition and the deep integration of digital technologies. These trends have led to the emergence of innovative mechanisms, such as P2P energy trading, supported by smart contracts, distributed ledgers, and flexible grid architectures.

The inclusion of multiple energy carriers within the P2P framework offers substantial advantages in terms of system flexibility, efficiency, cost-effectiveness, and environmental sustainability [176]. While electricity-based P2P models are well-established, growing attention is being paid to expanding these mechanisms to include other carriers such as thermal energy (heat), gas, and hydrogen. Integrating these vectors into a unified energy system can improve resilience and enable resource optimization at the community level.

The literature emphasizes that merging energy sectors—electricity, heating, gas networks, and mobility—contributes to higher technical and economic performance [15]. To evaluate such integrated energy systems (IES), there is a need for new analytical tools and transactive market mechanisms [16, 17].

As MES mature, P2P trading must also evolve beyond its electrical origins. This entails understanding how the inclusion of diverse energy carriers affects P2P market architecture, interoperability, and local energy balancing. Since households typically require electricity and heat simultaneously, exploring their interconnected trading behaviour under a P2P setting becomes critical.

Recent real-world pilot projects in district heating, hydrogen networks, and electric vehicle-to-grid integration (see Section 4.2 and Table 6) demonstrate that P2P trading is not limited to electricity and that practical implementations in other domains are underway. These developments confirm the technical feasibility of multi-vector P2P energy trading and justify its continued research and discussion in this context.

4.2 | Related Works

4.2.1 | Theoretical Foundations

P2P energy trading has expanded beyond electricity to multiple energy carrier systems covering heat, gas, and even transportation sectors. This expansion has triggered efforts to explore P2P trading models for IESs where different energy carriers, such as electricity, heat, and gas, can be operated together. This approach has been developed to increase energy efficiency, improve economic performance, and support low-carbon energy systems to enable the interaction of energy carriers. In this framework, P2P energy trading is critical in making energy systems more sustainable and efficient by increasing flexibility and interaction between energy carriers. A comprehensive literature review on this topic is presented below.

4.2.2 | Real-World Pilot Projects

In addition to these theoretical insights, several real-world pilot projects have emerged in recent years, offering concrete examples of P2P trading in heat, gas, and transport. These initiatives are described below with relevant references, demonstrating the tangible implementation of P2P principles beyond electricity:

4.2.2.1 | Heat. Real-world applications such as the Royal Docks project in the UK [177], the Framingham underground thermal loop in the USA [178], and the HYPERGRYD initiative under Horizon 2020 [179] have enabled localized thermal exchanges. These initiatives utilize bilateral agreements,

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predictive control, and decentralized thermal grids that operate with minimal central coordination—hallmarks of the P2P approach.

4.2.2.2 | Gas and Hydrogen. The E.ON Hanse power-to-gas pilot in Falkenhagen and Thüga Group's hydrogen injection scheme in Frankfurt, Germany [180, 181], show how hydrogen can be generated, injected, and traded among peers via shared infrastructure, blockchain-based contracts, and peer-led balancing mechanisms.

4.2.2.3 | Transport. Projects like Toyota's V2G demonstration in Japan [182], China's 9-city smart EV pilot [183], and the Oakland Unified School District's V2G electric school bus system [184] allow vehicles to function as active energy nodes. These setups support EV-to-EV and EV-to-building energy transfers in a peer-coordinated fashion.

4.2.3 | Challenges and Research Gaps

Traditional P2P trading has been extended to heat and electricity P2P transactions with integrated demand responses. Regional IES has dramatically improved the overall economic viability by enabling P2P exchanges of electricity and heat among multiple energy providers [19]. Research has been conducted on a non-cooperative game-based price clearing model and cooperative games for energy sharing between multiple regions; however, more must be done to determine transaction prices [185]. The primary obstacle that arises in the context of multi-energy operations is reaching an agreement and establishing the market price. Nash bargaining effectively coordinates interests and supports Pareto optimality and individual rationality [186]. A Nash bargaining model on electricity, heat, and gas transactions for multiple integrated energy service providers was developed, but it still needs to address how to ensure low-carbon systems [187]. Though they looked at heat, electricity, and hydrogen collaboration, [18] narrowed their attention to the electricity trade. A group of researchers proposed a mechanism based on a multi-leader Stackelberg game for electricity and heat, motivating participants with different pricing, but collaboration was not considered [188]. In another study, they integrated electricity and heat trading between commercial and residential communities using a Nash game for fair pricing [64].

However, despite these advancements, several challenges and gaps necessitate further investigation. The study in [189] examined the combined effects of multiple energy connections and cooperative behaviours in the P2P market, but it overlooked multiple peer cooperation. This highlights the need for a more comprehensive approach in future research. A multi-energy trading system covering electricity, cooling, and heat energies has been proposed between both commercial and residential buildings [64]. Decentralized thermal networks help to reduce heat loss in local networks and prevent energy losses over long distances [190], while the potential of heat prosumers to supply heat to thermal networks has been verified [191]. The current network does not support reverse consumer heat supply to the central thermal grid [192]. The P2P electricity-thermal energy trading market is a promising approach to promote local energy trading [193]. Moreover, a P2P electrical thermostatic energy trading model that considers energy loss and a P2P trading model to manage transactions between small-scale heat prosumers have been proposed [194].

Looking ahead, including new energy vectors such as hydrogen further complicates but also enriches the landscape of P2P energy trading. Peer-to-gas (P2G) technology for natural gas production may prove uneconomical due to the inefficiencies inherent in P2P trading of electricity and gas. Conversely, peer-to-hydrogen (P2H) technology demonstrates greater efficiency than P2G, offering a more economically viable solution for enhancing the profitability of P2P trading [195]. Hydrogen supports achieving the "double carbon" goal through power generation and blending with natural gas [196]. The impacts of hydrogen-infused natural gas on domestic and commercial gas appliances [197] and the integration of hydrogen blending into power plant schedules [198] have been studied.

However, studies in MES have focused more on electricity and heat, while gas P2P processes still need to be studied. In P2P MES, research predominantly centres on electricity and heat P2P processes, leaving gas P2P processes underexplored. This imbalance highlights a significant gap in the literature that must be addressed to leverage the potential of multi-energy systems fully. Moreover, the efficient and effective integration of gas P2P processes could significantly enhance these systems' overall functionality and resilience.

Integrating gas-blended hydrogen opens up new possibilities for electricity-heat-hydrogen multi-energy P2P transactions. This innovative approach enhances system efficiency and promotes the adoption of cleaner energy sources, thereby contributing to the broader goals of sustainability and carbon reduction. Given that natural gas and hydrogen can mix, load-generated hydrogen can be handled as a P2P transaction object, providing new avenues for energy exchange [20]. The energy-generating patterns of various microgrids are crucial for P2P energy trade and transformation within a local community. A new P2P energy trading and conversion system for several connected multi-energy microgrids has been proposed, further emphasizing the potential of integrated approaches in enhancing local energy resilience and sustainability [199].

To provide a concise overview of these real-world initiatives, Table 6 below summarizes key pilot projects across heat, gas/hydrogen, and transport sectors that demonstrate practical P2P energy sharing models.

In conclusion, addressing the existing gaps and embracing multi-energy P2P processes can lead to more robust, flexible, and environmentally friendly energy systems, ultimately leading to a smarter and greener energy future. The increasing number of real-world pilot implementations reinforces the notion that multi-vector P2P systems are no longer speculative but represent an emerging practical reality. and embracing multi-energy P2P processes can lead to more robust, flexible, and environmentally friendly energy systems, ultimately leading to a smarter and greener energy future. The increasing number of real-world pilot implementations reinforces the notion that multi-vector P2P systems are no longer speculative but represent an emerging practical reality.

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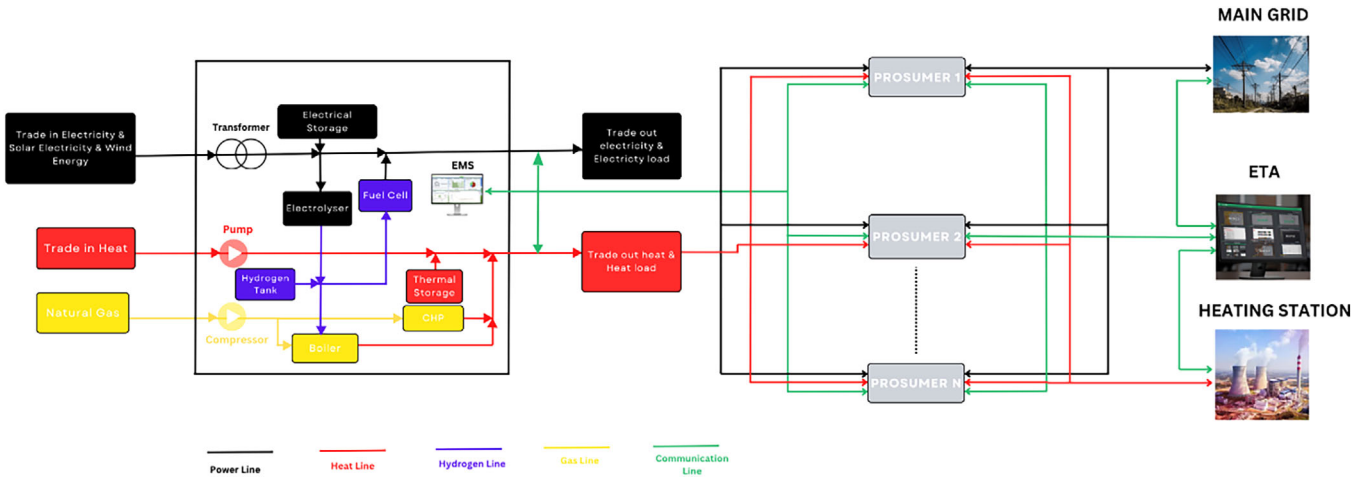


FIGURE 7 | Overall architectural structure of multi-energy carrier systems in integrated energy systems.

4.3 | System Model

4.3.1 | Infrastructure and Architecture

Within an IES, P2P multi-energy trading can be realized through infrastructures that provide participants access to different energy carriers [200, 201]. Electricity grids function as the fundamental infrastructure for conducting electricity trading, whereas natural gas markets are specifically designed to facilitate transactions involving natural gas. District heating networks and domestic heating systems are essential for heat exchange. Combining heat pumps and renewable energy sources in 4th generation heating systems enables effective temperature regulation down to 35°C. The 5th-generation systems aim to create a dynamic market for heat exchange across active substations. This will promote a market-driven approach to heat trading [202].

The general architecture of multiple energy carrier systems in an IES is shown in Figure 7.

4.3.2 | Flexibility, Modelling, and Control

Real-world pilots, such as the Framingham cooperative heating network and the Oakland electric school bus fleet, have demonstrated how P2P-compatible architecture can be integrated into local energy systems. In Framingham, smart control enables distributed thermal balancing, while Oakland's V2G buses showcase autonomous dispatch in peer-based transport networks.

Recent studies have increasingly highlighted the potential for small-scale P2P trading networks to contribute to broader grid services. While individual prosumer actions may be limited in scale, their collective impact—when aggregated and coordinated—can support peak shaving, load balancing, and voltage/frequency regulation.

One of the most cited field examples is the Brooklyn microgrid (USA), where P2P trading among households and businesses led to reduced peak demand through localized energy matching and demand-side flexibility. The platform also enabled participants to prioritize local trading over grid import, which indirectly alleviated stress on the main grid during peak hours [50].

In Fujisawa Sustainable Smart Town (Japan), residents equipped with solar panels and home energy management systems (HEMS) engaged in local energy exchange. The project integrated P2P coordination with neighbourhood-level batteries, supporting both resilience and time-shifted consumption, thereby flattening peak curves and enhancing self-consumption [203].

From a theoretical perspective, Morstyn et al. demonstrated that P2P aggregations can be structured as federated power plants, where prosumers coordinate through decentralized algorithms to act like virtual utilities. These federations can participate in demand response markets, providing ancillary services such as fast frequency response [47].

In Germany, the Pebbles Project (P2P Energy Trading with Blockchain) validated that real-time local trading can reduce reliance on transmission grids and optimize decentralized generation, which reduces system peak [67].

In summary, while traditional grid services are designed for centralized control, distributed P2P networks are increasingly capable of mimicking these functionalities through intelligent aggregation, demand flexibility, and price-based coordination mechanisms. This growing body of evidence suggests that small-scale P2P systems—when properly orchestrated—can indeed support grid stability and resilience. In Framingham, smart control enables distributed thermal balancing, while Oakland's V2G buses showcase autonomous dispatch in peer-based transport networks.

As energy storage technologies like heat pumps and hydrogen fuel cells advance, MES become more reliable and flexible power grids. This allows P2P energy trading to benefit from the maximum flexibility MES provides. However, understanding and quantifying the flexibility offered by P2P energy trading and MES is a complex task.

In modeling MES and P2P energy trading, intricate relationships are observed across various energy infrastructures like electricity,

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heat, and gas. This modeling approach addresses uncertainties in energy supply and demand dynamics, which are particularly relevant in today's rapidly evolving energy landscape. Understanding how P2P energy trade and energy transition initiatives can comprehensively support microgrids is crucial, especially considering the growing emphasis on renewable energy integration and the need for flexible and resilient energy systems [204].

Solar panels and wind turbines generate electricity, while excess energy can be stored in storage systems. Hydrogen production occurs by electrolyzing water and can be used with fuel cells or boilers to produce power and heat [205]. Natural gas can be deployed as an alternative fuel to meet heat demand. Using hydrogen fuel in low-carbon electricity, heat generation, and transportation offers diversity for future energy solutions. However, residential hydrogen use is still at a nascent stage. Institutional investments and hydrogen infrastructure development could lower hydrogen costs [206]. Water electrolysers can be used to address extra needs for heat and power; the hydrogen produced can be stored in hydrogen tanks until needed.

Conversely, certain storage technologies, like batteries, lose energy over time and require frequent recharging. Because water electrolysers can overcome these drawbacks, they provide an appealing alternative for storing hydrogen [207]. Combined heat and power systems meet demand and improve energy efficiency by producing electricity and thermal energy together. and embracing multi-energy P2P processes can lead to more robust, flexible, and environmentally friendly energy systems, ultimately leading to a smarter and greener energy future. The increasing number of real-world pilot implementations reinforces the notion that multi-vector P2P systems are no longer speculative but represent an emerging practical reality.

4.3.3 | Energy Conversion Efficiency, Storage Technologies, and Sector Coupling

The effectiveness of peer-to-peer (P2P) multi-energy systems is largely determined by how efficiently energy can be converted across vectors, stored, and exchanged through integrated infrastructures. In recent studies, the interdependencies between electricity, heat, and gas systems have revealed that technical optimization in one domain directly affects flexibility and stability in others. Therefore, evaluating conversion efficiency, storage performance, and sector coupling not as isolated technologies, but as interlinked system functions is critical for both operational performance and climate targets.

In terms of energy conversion efficiency, recent work emphasizes that the shift from mono-vector to multi-vector energy exchange introduces new constraints and possibilities. For instance, electricity-to-heat conversion via heat pumps has been widely studied in district heating and smart building contexts. Heat pumps exhibit high coefficients of performance (COP) between 3.0 and 4.5 depending on the temperature gradient, making them significantly more efficient than resistive heating, especially when powered by PV-supplied electricity in cooperative systems [205]. Similarly, the integration of combined heat and power (CHP) units into MES frameworks has been shown to improve overall exergy utilization. In [206], micro-CHP systems using natural gas or hydrogen achieved total system efficiencies exceeding 85%, particularly when waste heat was captured and reused within local thermal networks. These configurations align well with the cooperative P2P model, where energy flows are optimized for collective benefit rather than individual utility.

When it comes to energy storage, the literature reveals that storage technologies in P2P MES are more than passive buffers; they act as dynamic enablers of sectoral synchronization. Electrochemical batteries, such as lithium-ion or sodium-ion, remain dominant for short-duration balancing due to their fast response times and high round-trip efficiencies (~90%), but their role is limited in seasonal applications. In contrast, hydrogen-based storage systems, which rely on water electrolysis and fuel cell reconversion, are increasingly used for inter-seasonal flexibility. In [207], a cooperative P2P microgrid model demonstrated that integrating hydrogen storage increased self-sufficiency by 30% compared to battery-only configurations, particularly under variable renewable generation. Moreover, latent thermal energy storage using phase-change materials (PCMs) has been integrated into district-level P2P trading systems to enable low-temperature heat exchanges with stable discharge characteristics, reducing peak load in heating networks by up to 20% [191]. These results underline that choosing the right storage technology in MES is not solely based on energy density, but on synchronization potential across sectors and time scales.

Sector coupling, or the functional integration of electricity, heating, cooling, and gas infrastructures, forms the backbone of a technically robust MES. Studies such as [202] show that coupling electricity with heat through 5th-generation district heating systems allows low-temperature heat pumps to operate using renewable electricity, while waste heat from CHP or electrolysis processes can be reinjected into thermal loops, creating feedback-driven local ecosystems. Peer-to-hydrogen (P2H) models, examined in [195] and [20], further expand this potential by enabling renewable electricity surpluses to be converted to hydrogen and injected into decentralized gas networks. These hydrogen vectors were found to outperform methane-based power-to-gas approaches in both efficiency and lifecycle emissions. Integration with electric vehicle fleets also plays a growing role in MES. As demonstrated in the V2G-enabled school bus project in Oakland [67], mobile storage units can participate in real-time P2P balancing, with buses discharging during peak grid demand and recharging during low-cost surplus periods—an example of mobility-electricity coupling in practice.

Furthermore, the control and coordination of these sectoral interactions require advanced EMS equipped with multi-objective optimization algorithms. Systems described in [204] employ distributed model predictive control (DMPC) to balance electricity, heat, and gas flows across residential and commercial nodes. These platforms factor in carbon intensity, time-of-use tariffs, and DER availability to dynamically allocate energy across sectors. Especially in community-driven P2P setups, such algorithms help achieve local energy autonomy while supporting grid-level services like peak shaving and voltage regulation.

In conclusion, the engineering realization of MES-based P2P trading hinges on aligning conversion technologies, selecting

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context-appropriate storage systems, and enabling real-time sectoral coordination. The literature increasingly reflects this systems-level approach, where technology choices are evaluated not only for their standalone performance but for how they contribute to cross-vector optimization, resilience, and sustainability in decentralized energy communities.

5 | Conclusion

This comprehensive review of P2P energy trading highlights its transformative potential to democratize the energy system, boost efficiency, and meet sustainability goals in the context of increasing renewable energy integration and the evolution of innovative grid technologies. The paper provides an in-depth analysis of the current research landscape, focusing on five critical components:

1. Market mechanisms in P2P energy trading markets.
2. Operational layers involved in P2P energy trading.
3. Challenges encountered in the physical and virtual layers of P2P trading and technical solutions.
4. The role of P2P energy cooperatives.
5. Integration of P2P energy trading into multi-energy systems.

Each component is thoroughly examined, with existing studies reviewed in detail and future research directions identified. This review underscores the immense potential of P2P energy sharing, portraying it as a burgeoning field ripe with opportunities for both academic inquiry and industrial application. It is anticipated that this paper will offer novel insights into the design of pricing mechanisms for P2P energy trading and play a pivotal role in creating sustainable and efficient P2P markets within distribution networks. The insights from this review aim to inspire future research and innovation, driving the development of robust and resilient energy trading ecosystems.

Author Contributions

Zeynep Tanis: investigation, writing – original draft. **Ali Durusu:** conceptualization, methodology, supervision, writing – review and editing. **Nihan Altintas:** writing – original draft, writing – review and editing.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

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

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