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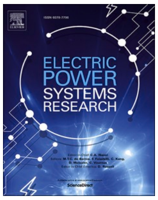

Peer-to-peer energy trading in smart grid: Frameworks, implementation methodologies, and demonstration projects

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ABSTRACT

Energy sector is undergoing a massive transformation that includes key aspects such as integrating renewables, improving operational efficiency, leveraging smart grid infrastructure, and handling the dynamics of transactive energy; all of which necessitates ecosystem players to refine their role, devise efficient regulatory/policy frameworks, and experiment with new business models. Given these circumstances, Peer-to-Peer (P2P) energy trading appears to be one of the viable solutions in which an end-user can sell/buy power to/from other users instead of fully relying on the utility for the same. However, the implementation of P2P energy trading in the distribution networks introduce new challenges, such as network constraint violations, increased communication requirements, compromised end-user privacy, the threat to the financial viability of the utility companies, etc. Various pilot projects and research are being carried out at different levels worldwide in this regard. This paper provides a detailed analysis of the existing research and implementation activities on P2P energy trading, and suggests potential future research avenues. Readers gain an understanding of P2P energy trading frameworks, implementation methodologies, and demonstration projects through this article.

1. Introduction

Widespread adoption of small-scale Renewable Energy Sources (RES) is crucial in modern power systems in order to achieve energy sustainability and reduce the environmental impact of electricity generation [1]. Through research and technological advancements, continuous efforts are being made to lower the cost of RES. Many governments have already begun to increase the penetration of renewable energy sources by enacting policies and implementing various support schemes. For example, India has launched the Grid Connected Rooftop Program, with the goal of achieving 40 GW of solar power from rooftop solar PV systems by 2022 [2]. Feed-in-Tariffs (FiT), import duty reductions, special loans, renewable energy mandates, green certificate trading, green purchasing preferences or environmentally preferred purchasing, and competitive bidding are examples of various RES policies and support schemes [3]. However, the most popular and proven mechanism for encouraging RES penetration is the FiT, in which the owner of a Distributed Energy Resource (DER) is guaranteed a minimum price for electricity generation [4].

In addition to covering the cost of production, FiT may also include a bonus amount to encourage investment in DERs [5]. However, as the deployment of DERs grows in terms of both the number of installations and total installed capacity, the FiT rates are expected to undergo major revisions [6]. For example, the UK government proposed lowering the solar PV generation tariff for new applicants beginning in January 2016 [7], and the effects can be seen in the FiT rates available on their gas and electricity market regulatory authority portal [8]. The changes in the FiT rates have diminishing effects on the benefits received by the DER owners [9]. Users are less likely to install DERs due to these concerns, and the goal of reducing carbon emissions may take much longer than anticipated. In the meantime, a new form of energy trading mechanism known as Peer-to-Peer (P2P) energy trading has emerged, which can be viewed as the successor of FiT scheme [10]. P2P energy trading enables DER owners (prosumers) to sell their excess energy to other consumers or prosumers at a higher rate than FiT. On the other hand, consumers gain access to energy at a lower cost in a competitive market, with the freedom to choose their energy supplier. This process also ensures that consumers receive a reliable and consistent power supply. As a result, local energy markets based on peer-to-peer energy trading benefit both prosumers and consumers. Furthermore, peer-to-peer energy trading is effective in reducing line losses and deferring costly network upgrades [11,12]. Many governments are also conducting pilot projects in order

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to make this new energy trading scheme operational in the near future. For example, the Uttar Pradesh Electricity Regulatory Commission in India issued a tariff order encouraging state distribution licensees to implement more P2P energy trading pilot projects based on the results of their first blockchain-based P2P solar power trading pilot project [13].

Many researchers and engineers are attempting to address numerous challenges associated with the consumer-centric P2P energy trading mechanism as this research topic is fresh to the literature. The following are some of the studies that have been published in the literature. The authors of [14] attempted to develop a utility-operated P2P energy trading mechanism that did not require any additional changes to the existing distribution infrastructure. Tushar et al. [15] describe a battery scheduling-based P2P energy trading architecture developed using the game theory. In [16], a deregulated P2P energy sharing mechanism was reported, which is free from utility interference and uses blockchain technology. Using game theory, the authors of [17] attempted to build a P2P trading approach for virtual microgrids. A joint P2P trading framework in the presence of fluctuating energy resources and Electric Vehicles (EV) has been presented in [18]. An assessment of P2P energy trading in the grid-connected system considering the network constraints is presented in [19].

Based on the variety of articles offered in [14–19], it can be concluded that the research on P2P energy trading is gaining attraction. As a result, we have attempted to provide a comprehensive review of the seminal contributions made by various research groups in the field of P2P energy trading in this paper. The discussion in this article differs from that found in the previously published review articles on the topic. For example, [20] provided a systematic and comprehensive description of P2P energy trading. The authors examined a variety of topics but did not provide information on implementation initiatives. In [21], different optimization objectives and market clearing mechanisms used in the design of local energy markets are discussed. However, the information about the various steps involved in such energy markets and their real-life implementation is missing. Similarly, Esteban et al. highlight the current approaches, challenges, and future research directions associated with the P2P energy trading in [22] without focusing on the mathematical aspects of the problem formulation. Considering the aforementioned topics which are not covered in the literature, the contributions of this review paper can be summarized as follows:

- In addition to providing a comprehensive overview of P2P energy trading frameworks, this article addresses the mathematical formulations as well as discusses about the several P2P pilot projects taking place across the globe. As a result, this article provides information about the work being done at both the academia and industrial levels, which is most likely the first attempt.
- The paper presents the layered architecture of P2P energy trading, classifies the trading frameworks based on the market mechanism, and describes the generalized steps involved in this novel energy sharing paradigm. Having the aforementioned details in a single article help the researchers better grasp the concept of P2P energy trading without searching for each topic individually in literature.
- As the information about the P2P energy trading testbed being developed at the Indian Institute of Technology Gandhinagar is also provided, this article gives insights to the engineers about developing the same at their facility. In a broader sense, the topics discussed in this manuscript are helpful to both scholars and engineers, which is yet another noteworthy contribution.

The paper is organized in the following way. Section 2 discusses the different structures of P2P energy trading, while the steps involved in P2P energy trading are presented in Section 3. Methodologies commonly encountered in the recent literature to implement P2P trading frameworks are reviewed with their mathematical formulations in Section 4 of the paper. Section 5 gives an overview of the use cases and real-world implementations of P2P energy trading. Finally, the paper concludes after providing some directions which are open for future research work.

2. Structure of P2P energy trading

In this era of decentralized energy trading, generation units and large-scale energy consumers can very well participate in the wholesale markets under the guidelines of transmission system operators. However, it is unrealistic for the end-users connected through the low voltage distribution networks to participate in the wholesale markets regulated by transmission companies [23]. From the aforementioned literature, it is clear that P2P energy trading is predominantly performed at distribution networks. The pictorial representation of P2P energy trading framework is shown in Fig. 1.

As illustrated in Fig. 1, the P2P energy trading requires a robust distribution network to realize local energy transfers. On the other hand, in order to make the trading effective, a communication network that can broadcast the preferences of the prosumers is also required. Therefore, it can be said that for the efficient implementation of P2P trading, the physical layer alone will not be sufficient. The layered architectures for seamless transfer of power, data, and other control signals for making P2P energy transfer more attractive are presented in [24] and [25]. A generalized pictorial representation of the same is depicted in Fig. 2.

The physical layer in Fig. 2 is similar to a power grid where the power system asserts are present. In this layer, the power generation, monitoring, metering, and other supportive equipments which are required for the transfer of electrical energy will be placed. The second layer from the bottom is the ICT layer which is like a semi software layer where communication devices like switches, transceiver with necessary software will be working as per the standard communication protocols. This layer essentially handles the data being transferred in the network. The control layer is mostly handled by the distribution system operators wherein various control actions are undertaken so as to keep the energy transfer corridor efficient and reliable for trading. The business layer is where P2P energy trading decisions are taken. It involves consumers, prosumers, and different entities who participate in trading. The entities sitting in this are governed by the regulatory framework of the market, essentially through a government policy. The top layer labelled as an application layer provides a user interface to communicate preferences and results of P2P energy trading.

The market mechanisms residing in the business layer of Fig. 2 also plays a crucial role in defining the nature or type of P2P energy trading [10]. As depicted in Fig. 3, the P2P energy trading can be classified in three categories namely centralized, decentralized, and distributed based on the type of market mechanism used.

In a *centralized energy market*, different peers interested in trading will communicate their requirements or willingness to a central entity. The central entity, in turn, decides the quantum of energy transfer, buying and selling prices and distributes the revenue among the peers [26]. The complete information availability at the central point results into the maximum overall social welfare of the P2P community compared to distributed and decentralized approaches [27]. On the other hand, this approach burdens the communication infrastructure because everything has to pass through a single entity. As all peers share their data with the system operator, their privacy may be at risk.

The *decentralized energy markets* do not have any kind of central utility to coordinate the trading. In this case, the trade is conducted between the peers individually without any intervention of the third party, and hence the privacy of the peers is well protected [28]. Also, the

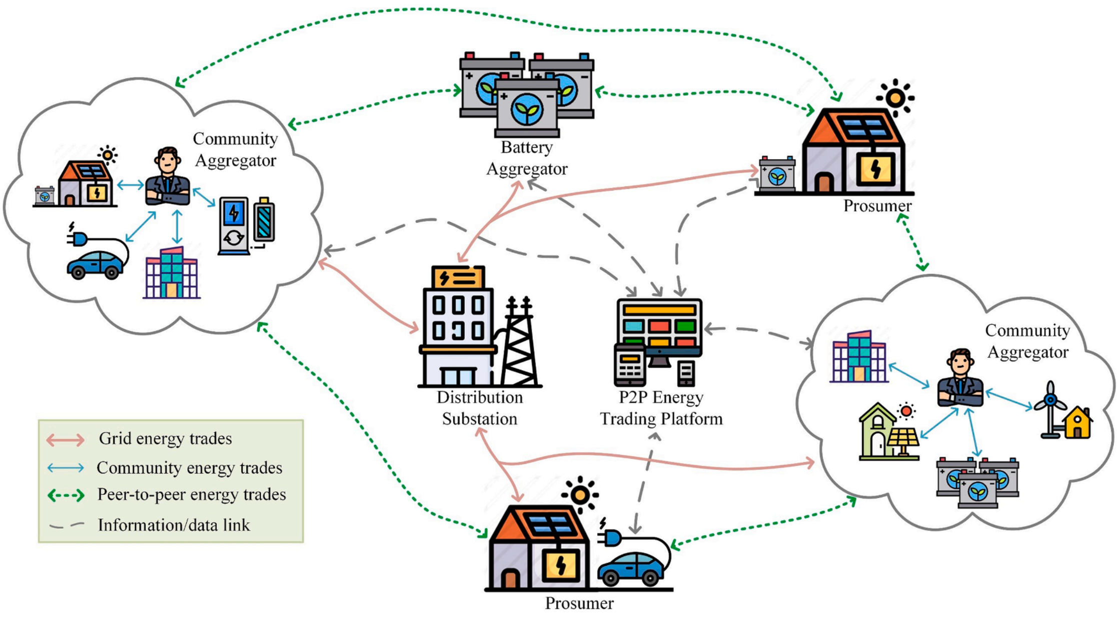
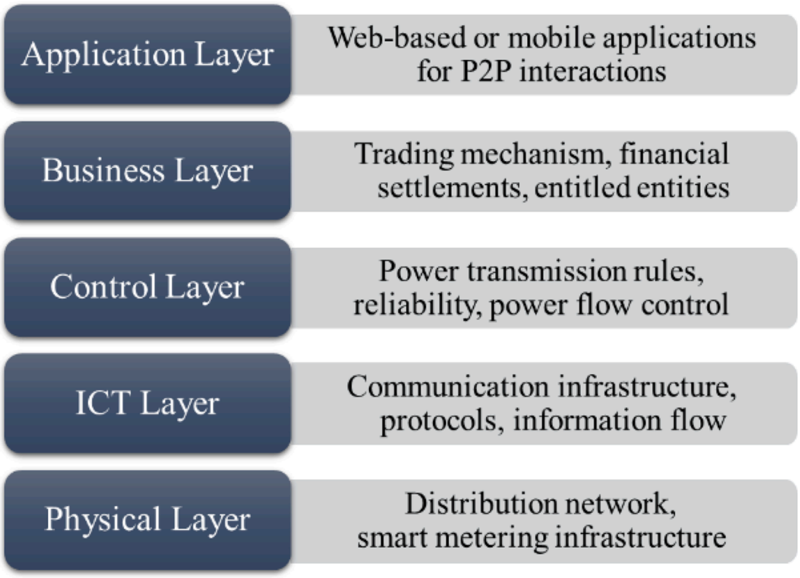


Fig. 1. Pictorial representation of P2P energy trading framework.

peers are completely independent in controlling their appliances. Further, as the distribution operator is not involved in the trading process, it becomes difficult for the utility to schedule their resources which may result in reduced operational efficiency of the distribution system. This methodology also leads to reduced social welfare of the P2P community as the individual interests are prioritized over the community welfare [23].

Distributed energy markets are a hybrid version of both the other markets. In this trading technique, the central utility is involved in an indirect way. The system operator will be communicating price signals to the peers so that they can make out a schedule independently [29]. This results in increased privacy in the prosumers as well as better understanding within the peers. In this market mechanism, the distribution system can also be operated in a better way in comparison to the decentralized markets [30].

Further, in order to buy or sell energy and to participate in P2P trading, each peer shown in Fig. 3 should be equipped with a variety of flexible loads, energy storages, and generation resources. The architecture of an ideal peer consisting of different assets which enable efficient participation in P2P energy trading is shown in Fig. 4 [31]. It is suggested that the peers reduce their demand by effective management of loadduring the peak hours of the day along with optimal scheduling of available generation and energy storage resources in order to reap the maximum economic benefits via P2P trades. In this regard, the smart agent is essential as it uses the historical data and machine intelligence-based decisions to optimally schedule the flexible resources



Application Layer	Web-based or mobile applications for P2P interactions
Business Layer	Trading mechanism, financial settlements, entitled entities
Control Layer	Power transmission rules, reliability, power flow control
ICT Layer	Communication infrastructure, protocols, information flow
Physical Layer	Distribution network, smart metering infrastructure

Fig. 2. Different layers of P2P energy trading.

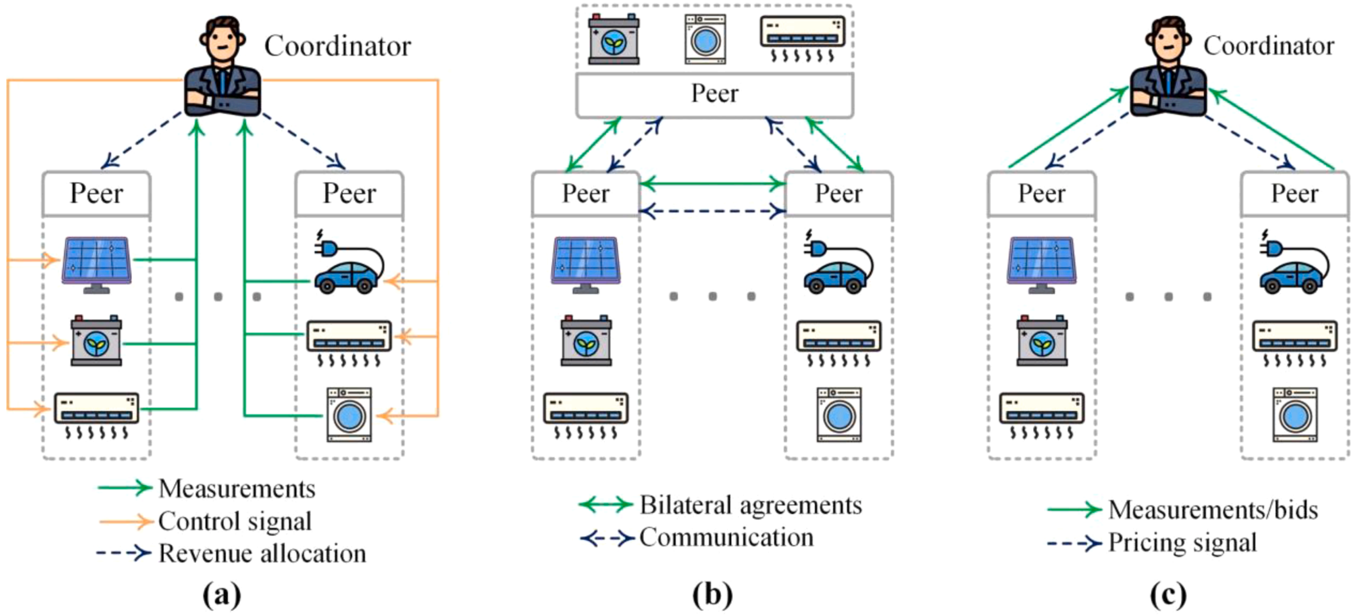


Fig. 3. Classification of P2P energy sharing frameworks based on the types of the market mechanism: (a) centralized, (b) decentralized, and (c) distributed.

of the peers participating in the P2P energy trading. A smart agent is essentially a microcomputer device with adequate data storage and processing capability to execute a variety of functions. It can handle activities such as electricity price and load demand forecasting, home energy management, optimal DER scheduling, optimal automated bidding in P2P energy trading platforms, and demand response program-based appliance control. The smart agent also eliminates the need to replace conventional energy meters with smart meters in order to participate in emerging energy schemes such as P2P energy trading and demand response. Moreover, it can operate as a gateway between the energy meter and databases, such as blockchain, for storing data in a safe manner. Section 5.4 of the paper discusses a real-world implementation of the smart agent at the P2P energy trading testbed of the Indian Institute of Technology Gandhinagar.

3. Steps involved in P2P energy trading

As shown in the previous section, P2P energy trading involves different stakeholders such as prosumers, consumers, aggregators, and systems operators at various levels. The roles of these stakeholders in P2P energy trading can be understood by looking at the various steps involved in the trading process. Fig. 5 shows a pictorial representation of the steps involved in implementing and availing the benefits of P2P trading, while a brief overview of the same is provided in the subsequent text.

3.1. Registration / onboarding

The prosumers in the distribution network register the details of their

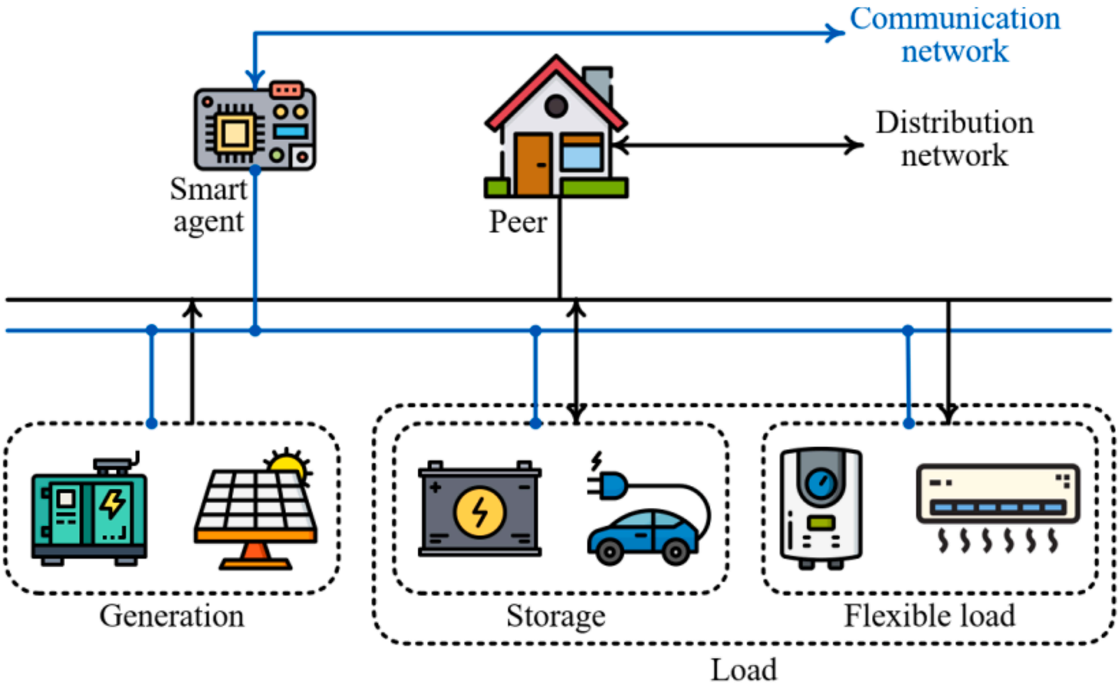


Fig. 4. The architecture of a typical peer.

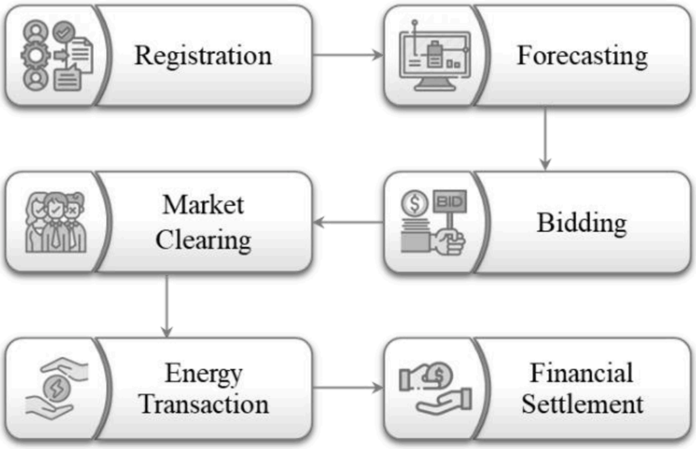


Fig. 5. Steps involved in a typical P2P energy trading.

generating assets and flexible demand to the entity assigned for conducting the P2P energy trades like an aggregator, Distribution System Operator (DSO), or P2P trader. The collected information can be used to onboard the prosumer for P2P trading by installing the net metering infrastructure, providing access to online platforms for bidding and financial settlements, executing various legal agreements, etc. Note that in the fully decentralized P2P energy trading platforms, it is being assumed that the prosumers are equipped with the necessary metering and communication infrastructure to participate in the P2P energy trading.

3.2. *Forecasting*

The prosumers interested in participating in the forward P2P energy market first forecast their local generation and demand. The forecasted profiles help the Energy Management System (EMS) located at the end-user premises to decide the quantum of energy to be traded in the P2P market and the quantum of energy to be used for fulfilling local demand at a particular time interval of interest in the future. To ensure a high forecasting accuracy, various methods have been proposed in the literature which can be broadly categorized into artificial intelligence and machine learning based forecasting, forecast combination and ensemble forecasting, hierarchical forecasting, and probabilistic forecasting [32].

3.3. *Bidding*

Based on the net import/export decided to trade in the P2P market in the previous step, the prosumer or EMS on behalf of the prosumer strategically places a bid highlighting the quantity and preferred price of energy to be bought or an ask representing the quantity and desired price of energy to be sold. A knowledge of bids and asks selected in the past can also help the prosumers or EMS to intelligently bid in the P2P market and maximize their qualification chances. Note that this step is only applicable to the auction-based P2P markets like the ones proposed in [31,33–44].

3.4. *Market clearing / peer matching*

The information related to the bids and asks from the prosumers are stored in an order book of the respective time interval. They are sorted based on the price, and then the market is cleared, highlighting the eligible prosumers for P2P energy trading. In general, the objective of market clearing mechanisms is to maximize the social welfare of all the participants while considering the distribution network constraints. In majority of the optimization and game theory-based formulations to be discussed in the next section, the quantity and price of energy to be traded among the peers is decided in a centralized or distributed manner using mathematical programming. In these methods, the concept of submitting bids and asks is not applicable as the allowed P2P trades are decided considering the available net import/export, the social welfare of the participants, and network constraints.

3.5. *Energy transactions*

In this step, the qualified peers start injecting or drawing power as per the P2P trades finalized after the market clearing process. The metering and communication infrastructure installed on the prosumers' premises in the onboarding stage facilitates the automated fetching and transfer of real-time meter data to the responsible entity. At the time of power delivery, if a prosumer is unable to inject the power as per the agreement, then the undelivered power will be supplied by the grid. In a similar manner, the deviations from the consumer-end energy consumption will be balanced out by the grid power. However, it is to be noted that a penalty will be imposed for deviating from the P2P energy trade agreement as discussed in the next step.

3.6. *Financial settlements*

The aggregator, P2P trader, or DSO confirms the successful execution of P2P trades by comparing the P2P market-clearing results with the energy meter data of peers on a particular time interval. If a peer is deviated in real-time from the submitted bid or ask, then a penalty is levied to discourage that type of behavior in the future. Hence, the financial settlement of P2P energy trades includes the charges for the power drawn or revenue for power injected, charges of deviation, network usage charges, and charges to account for the losses happening during the power transfer.

4. Implementation methodologies

4.1. *Game theory*

Game theory is a branch of applied mathematics that provides tools to model and predict the strategic behaviours of the rational and self-interested players in real-world competing scenarios like the game of chess and poker, the prisoner's dilemma, the formulation of political coalitions, bidding in an auction, and many more [45]. The solution of a game-theoretic problem provides the optimal strategies of the players and the resulting scenarios by adapting those strategies in the game. The games can be classified based on the number of players, availability of information, behavioural logic and rationality of players, types of strategy, and payoffs, as shown in Fig. 6 [46]. But mainly, it can be

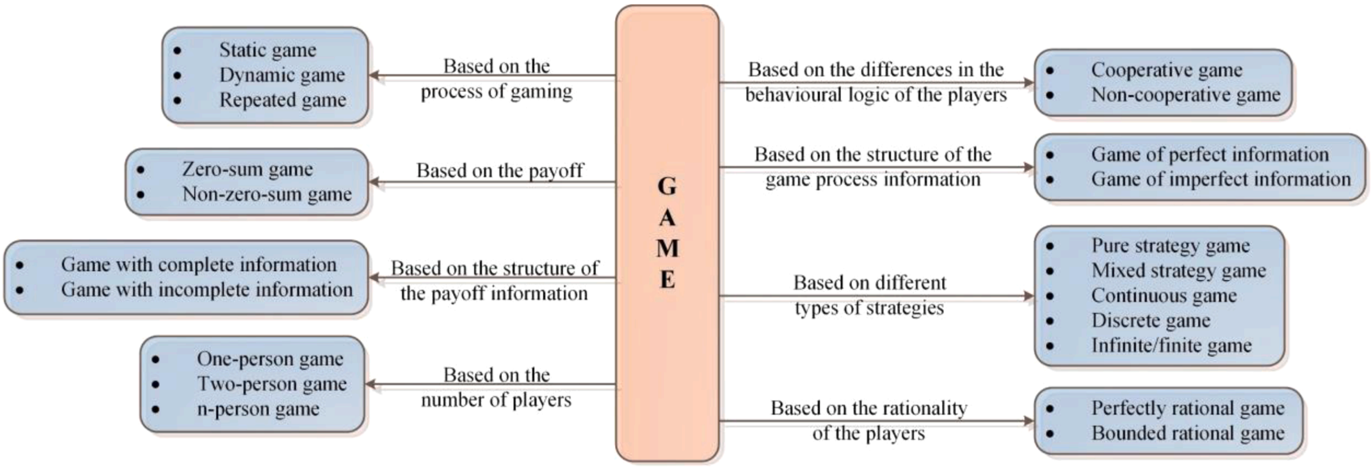


Fig. 6. Classification of different types of games in Game Theory.

divided into cooperative and noncooperative games.

4.1.1. Noncooperative games

Noncooperative games can be used to analyze competitive situations where the players have conflicting interests over the results of a decision-making process. It helps the players to optimize interdependent objective functions without any coordination or communication. Any cooperation in a non-cooperative game should also arise without any coordination of decision-making among the players [47]. Noncooperative games can be further classified into static and dynamic games. The players select the strategy and act at the same time in a static game, while actions are taken successively after determining the strategies in the dynamic games [48]. The solution of a non-cooperative game is a Nash equilibrium which is a state in the game where no player can improve its payoff further by changing its actions when the actions of the remaining players are fixed. Let, N is the total number of players and S_n is the strategy set of players $n \in N$, where S is the Cartesian product of the strategy set of each player that is $S = S_1 \times S_2 \times \ldots \times S_N$. Assume that the strategy chosen by each player n is $s_n \in S_n$, then the vector of strategies of N players can be defined as $s = (s_1, s_2, \ldots, s_N)$ and the vector of

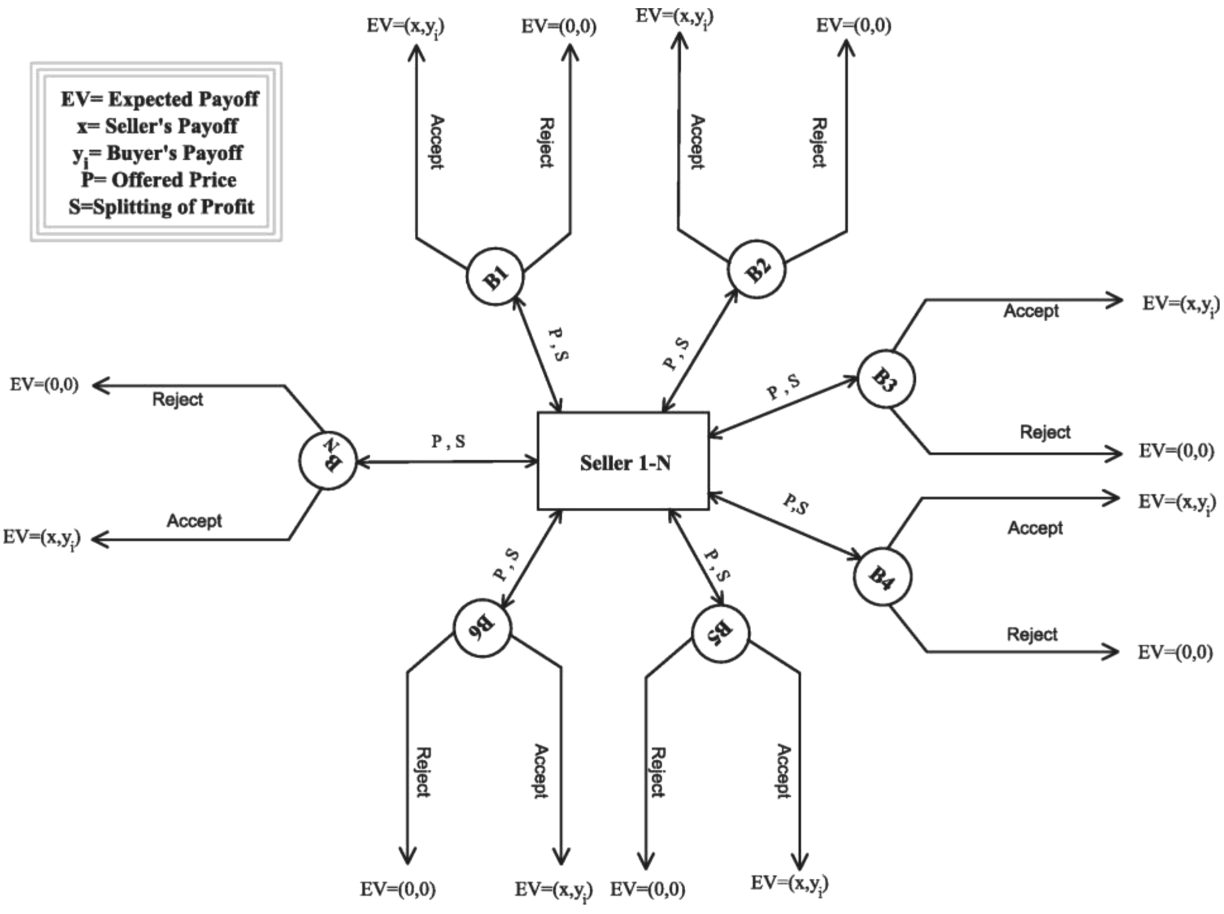


Fig. 7. Energy trading game proposed in [24].

corresponding payoffs can be defined as $U = (U_1(s), U_2(s), \ldots, U_N(s)) \in R^N$, where $U_n(s)$ is the utility of player *n*. With these declarations, the game can be represented in its strategic form as $\{N, (S_n)_{n\in N}, (U_n)_{n\in N}\}$ where each player choses its best strategy U_n^* to maximize its payoff. A strategy set $s^* = (s_1^*, s_2^*, \ldots, s_N^*) \in S$ is the Nash equilibrium if,

$$\forall n,\ s_n \in S_n\ :\ U_n\left(s_n^*, \bar{s}_n^*\right) \geq U_n\left(s_n, \bar{s}_n^*\right)$$

where, $\bar{s}_i = (s_1, s_2, \ldots, s_{i-1}, s_{i+1}, \ldots, s_N)$ is a vector of strategies of all participants excluding player *i*. In the case of multiple Nash equilibriums, an efficient and desirable solution of the game should be selected.

A peer-to-peer energy sharing among energy buildings equipped with renewable generation, energy storage system, controllable HVAC load, and uncontrollable loads is modeled as a non-cooperative game in [49] and [50]. In this game, each energy building is considered as a player who selfishly tries to optimize its cost function based on the energy sharing and payment-related decisions of other buildings/players. The mathematical model of the energy sharing game (Γ) is given in (1) where N denotes the set of all buildings, (x_n, π_n) is the strategy set of each building $n \in N$ within the constraint/feasible set Ω_n, and C_n denotes the cost function of building *n*. The strategy set of each building includes its energy schedule (x_n) and payments related to P2P energy sharing (π_n); while the cost function takes into account the discomfort cost of HVAC load (C_n^{HVAC}), degradation cost of ESS (C_n^{ESS}), cost of trading with utility ($C_n^{Utility}$), and payments related to P2P energy sharing (π_n) as shown in (2).

$$\Gamma := \left\{N, (x_n, \pi_n)_{n\in N} \in \Omega_n, C_n\right\} \tag{1}$$

$$C_n(x_n, \pi_n) = C_n^{HVAC} + C_n^{ESS} + C_n^{Utility} + \pi_n \tag{2}$$

Authors in [24] have also used non-cooperative game theory to determine P2P energy trading prices and to encourage sellers and buyers to participate in local energy trading. As shown in Fig. 7, the seller's strategy is the offered trading price (P) and the percentage distribution of profit (S) if the buyer (B) agrees to trade with him/her; while the buyer's strategy is to accept or reject the offers from the sellers to increase his/her expected payoff (y_i). Existence of strict Nash equilibrium was proved and it was shown that any deviation from the equilibrium will result in zero utility for both the seller and buyer. Similarly, as described in Table 1, the non-cooperative theory is used in [25] and [51–55] to model various types of interactions happening among the prosumers participating in P2P energy trading.

4.1.2. Cooperative games

Cooperative games, on the other hand, focus on the joint actions and collective payoffs of the players when they can communicate and cooperate with each other. The objective is to incentivize players to form coalitions and act together to achieve a public interest solution. Nash bargaining and coalition games come under this category of game theory. Nash bargaining focuses on the terms and conditions under which the players agree to cooperate, while coalition games deal with the creation of coalitions [56]. A value function v quantifies the value of a coalition $C \subseteq N_c$ where N_c is a set of players who want to form cooperative groups. Hence, the aim is to form coalitions C with maximum value $v(C)$ arising from them. The coalition games can be categorized into canonical coalitional games, coalition formation games, and coalitional graph game. The detailed explanation of these three types of coalition games can be found in [9].

Table 1
Summary of literature on noncooperative game theory in P2P energy trading.

Ref.	Objective
[25]	To simulate the P2P bidding in a single energy exchange time slot by deciding the status of flexible demand and/or generation of consumer and/or prosumer in the microgrid
[51]	To maximize the social welfare of the seller by determining the transaction price and transaction flexibility in P2P energy sharing based flexibility securing mechanism
[52]	To model price competition among the sellers whose aim is to maximize their own social welfare by selling a major portion of the excess power to the buyers in the P2P energy market
[53]	To clear the P2P energy sharing among the smart energy buildings in a manner that brings economic benefits compared to the traditional energy trading approach
[54]	To determine the electricity price and quantity for the seller based on the strategies of the other sellers participating in the multi-microgrid P2P energy trading framework
[55]	To develop a real-time pricing model for P2P energy trading between the prosumer acting as a leader and the consumer acting as a follower in the game

Authors in [57] have used a cooperative Stackelberg game to formulate a centralized power system-driven P2P energy trading framework. In the proposed model, the grid G acts as a leader and chooses a suitable energy selling price $\pi_{g,s}(t)$ as its strategy to reduce the energy trading with prosumers and motivate them to participate in the P2P energy trading when the total energy demand by the prosumers $E_D(t)$ is greater than the threshold $E_T(t)$ set by the grid. On the other hand, the prosumers in the set N act as followers in response to the price set by the grid. To balance his or her energy portfolio, each prosumer $n \in N$ chooses the amount $\varepsilon_{n,p2p}(t)$ and price $\pi_{p2p}(t)$ of energy as their strategies, participate in a double auction to be a part of different coalitions, and then trade energy in a P2P fashion within the respective coalition. Eq. (3) represents the Stackelberg game Γ in its strategic form where $U_n(t) \in \{U_{n,s}(t), U_{n,b}(t)\}$ is the utility of the prosumer n for trading its energy, as a seller or buyer, with other prosumers and grid at time t and $C_g(t)$ is the net cost to the grid for trading energy with the prosumer. The objective is to find the cooperative Stackelberg equilibrium of the game Γ by finding a set of strategies $(\pi_{g,s}^*(t), \varepsilon_{n,p2p}^*(t), \pi_{p2p}^*(t))$ such that the condition in (4) is satisfied and the prosumers' strategies $(\varepsilon_{n,p2p}^*(t), \pi_{p2p}^*(t))$ in response to the grid's strategy $\pi_{g,s}^*(t)$ forms a stable coalition structure

$$\Gamma := \left\{(N \cup G), U_n(t), C_g(t), \pi_{g,s}(t), \varepsilon_{n,p2p}(t), \pi_{p2p}(t)\right\} \tag{3}$$

$$C_g\left(\pi_{g,s}^*\right)(t) = 0 \tag{4}$$

Nash bargaining can provide a Pareto-efficient outcome in a fair manner and improve the economic advantages of the participants [58]. Considering this fact, authors in [59] have used a bargaining game to achieve cooperation among the prosumers to exchange energy in a P2P fashion and gain benefits. In the proposed two-stage problem, the first stage shortlists M out of total N prosumers to participate in the bargaining game based on whether they are contributing to improve the social welfare U_{sw} of the community or not. After that, in the second stage, the payment bargaining problem shown in (5) is solved to achieve optimal payoffs U_π and improved utility of the prosumers participating in the bargaining theory based P2P energy sharing. The problem modelled in (5) is subjected to the constraint in (6) and constraints from the first stage community social welfare maximization problem. Note that U_{p2p} and U_{ind} are the values of utility when the prosumer participates in the P2P energy trading and when they individually optimize their utilities, respectively. It was found that the prosumers were able to get more benefits while participating in the P2P energy trading compared to individually optimizing their payoffs.

$$\max \prod_{i\in M}\left(U_{\pi,i} + U_{p2p,i} - U_{ind,i}\right) \tag{5}$$

$$U_{ind,i} \leq U_{\pi,i} + U_{p2p,i} \tag{6}$$

Similarly, research work cited in [15] and [60–63] have also used cooperative game theory in the context of P2P energy trading. The summary of the literature on cooperative game theory in P2P energy trading is provided in Table II.

Table 2
Summary of literature on cooperative game theory in P2P energy trading.

Method	Ref.	Objective
Coalition formation game	[15]	To form stable and socially optimal cooperative groups among the prosumers and realize prosumer-centric P2P energy trading
	[60, 61]	To construct an energy coalition and cooperatively optimizing the prosumers' energy storage units so that they can gain the highest monetary benefits
Canonical coalition game	[62]	To form a grand coalition among the prosumers and incentivize them to participate in the P2P energy trading
Nash bargaining	[63]	To maximize the social welfare of distribution network operator, buyer, and seller considering the network constraints and to achieve fair profit allocation in the cooperative P2P energy market

4.2. *Double auction mechanism*

Double auction mechanisms are used as market-clearing mechanisms in the P2P energy trading frameworks where the matching of buyers and sellers interested in participating in the P2P trading is carried out. In the auction, within the gate opening to gate closure time of the P2P market, customers predicting energy deficiency submit the bid to buy energy, while the prosumers predicting excess energy submit an ask to sell energy at a particular timeslot *t* in the future. The bid from a consumer can be represented as $o_{b,t}(\varsigma_t,\ \pi_{b,t},\ \varepsilon_{b,t}, \tau_t)$ which shows that a consumer ς has submitted a bid at time τ to buy ε kWh of energy at a price of π_b Rs /kWh. Similarly, the asks submitted by the prosumers can be represented as $o_{a,t}(\rho_t,\ \pi_{a,t},\ \varepsilon_{a,t}, \tau_t)$ which shows that a prosumer ρ has submitted an ask at time τ to sell ε kWh of energy at a price of π_a Rs/kWh. After the gate closure time, the bids are ordered in the descending order of the bid price $\pi_{b,t}$; while the asks are ordered in the ascending order of the ask price $\pi_{a,t}$ as shown in Fig. 8. The intersection of two graphs gives the market-clearing price $\pi_{p2p,t}$ and market clearing volume $\varepsilon_{p2p,t}$ at which the market is cleared.

The authors in [64] proposed an ancillary service provision mechanism that can be used by the power system operator to get ancillary services from a P2P energy community. In the first stage of the framework, Continuous Double Auction (CDA) was used to facilitate P2P energy trading among the community members. The same CDA algorithm is also used in [34–36] for P2P energy trading. In these works, the prosumers decide the amount of energy to be sold/buy from P2P energy trading based on the net load profiles obtained from a home energy management system. Each prosumer is considered as a 'zero intelligence plus' trader who initially decides the price for bid/ask at random based on his/her budget and later dynamically alters it based on the matched bids/asks in the auction. In [31], an ideal double auction mechanism is defined as one which results in a non-negative utility for each participant, maximizes the total social welfare, incentivize truthful bidding, and does not lead to any loss for the auctioneer. Considering these four fundamental properties, a Vickrey-Clarke-Groves mechanism was used to eliminate market power and maximize social welfare in a

Table 3
Summary of literature on auction mechanisms in P2P energy trading.

Ref.	Objective
[38]	English auction mechanism coded in the blockchain smart contract to realize a transparent and adaptable P2P energy trading within virtual power plant framework
[39]	Iterative double auction mechanism to determine the price and amount of electricity to be traded among plug-in hybrid EVs such that maximum social welfare can be achieved
[40]	Uniform intraday auction and settlement mechanisms stored into blockchain smart contract to govern the P2P electricity exchanges enhancing the performance of classic pairwise settlement
[41]	Blockchain-assisted distributed double auction for P2P energy trade to mitigate the problems related to centralized double auction mechanisms
[43]	Double auction mechanism to achieve intraday P2P energy trading among residential houses and promote collaborative demand response schemes in the face of disturbances
[57]	Double auction to determine the members of the coalition that will trade energy with one another in a cooperative Stackelberg game based P2P energy trading

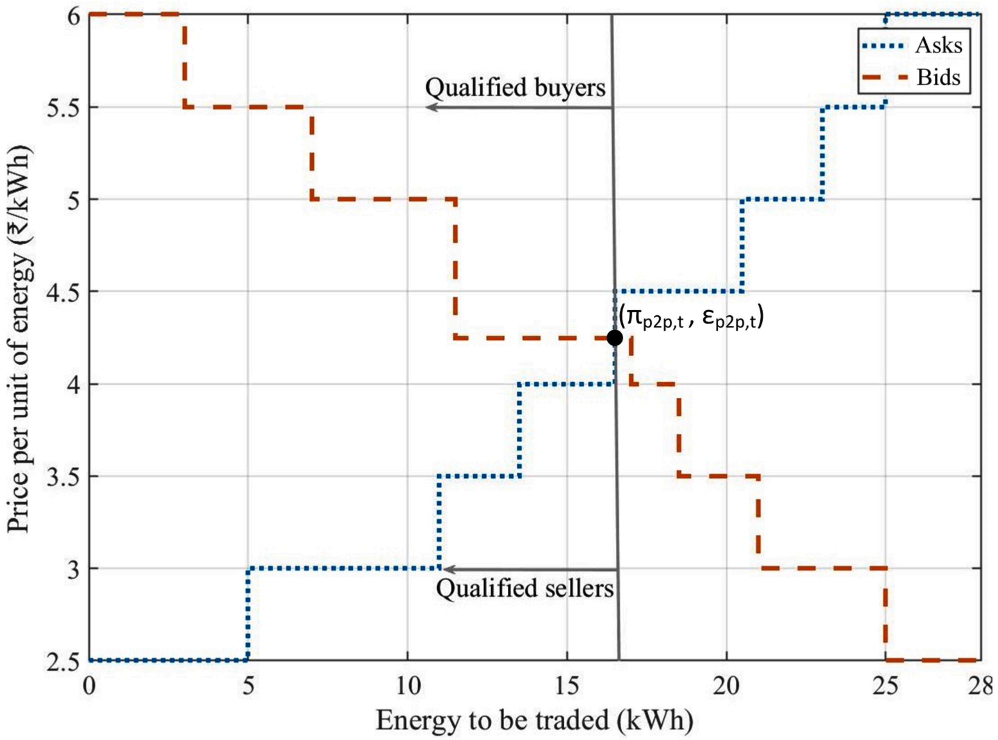
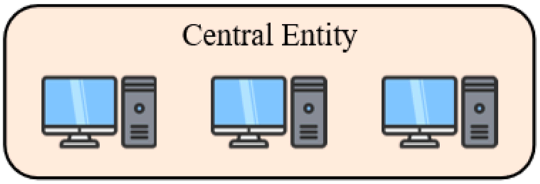


Fig. 8. P2P market-clearing through the double auction mechanism.

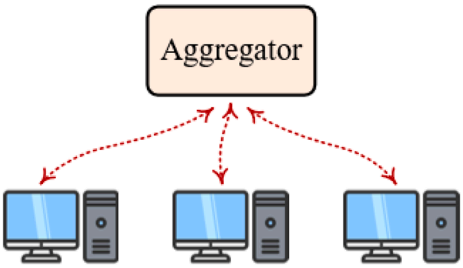
blockchain-based P2P energy trading market. Similarly, a real-time double auction market with a continuous bidding mechanism is used in [37] to realize local energy trading in an urban community microgrid system while enhancing the utilities of both the prosumer and the whole community. Further application of different auction mechanisms in the P2P energy trading can be found in [38–44, 57] as briefly highlighted in Table 3.

4.3. Optimization

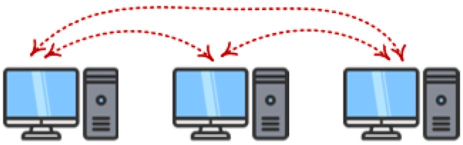
Optimization or mathematical programming is used to solve quantitative problems arising in various disciplines and real-world environments [65]. In particular, it helps in finding the optimal values $(x_1^*, x_2^*, \ldots, x_n^*)$ of decision variables $(x_1, x_2, \ldots, x_n)$ affecting an objective function $f(x_1, x_2, \ldots, x_n)$ needs to be minimized or maximized. The optimization problems can be broadly classified as continuous versus discrete, constrained versus unconstrained, stochastic versus deterministic, single-objective versus multi-objective, and linear versus nonlinear optimization [66]. On the other hand, they can also be divided into centralized, decentralized, and distributed optimization based on the architecture used to solve them [67]. In centralized optimization, the problem is solved by the centralized computing nodes having access to all the necessary data, as depicted in Fig. 9. The drawback of this approach is increased computation and communication requirements to solve large problems with multiple participants involved. Also, the privacy of participants is compromised as the central entity has access to the participants' sensitive data. In contrast, decentralized optimization has an aggregator to coordinate the computing nodes solving local subproblems at participants' end and then to achieve global solution of the problem using distributed consensus. The concept of aggregator is absent in the distributed or fully decentralized optimization problems where the participant nodes communicate directly with each other to achieve consensus. Hence, both the decentralized and distributed approaches reduce the computation requirements and protect the privacy of the participants. Now, with this background to various optimization techniques and considering P2P energy trading as an enabler to achieve decentralized energy trading among the prosumers, it can be implied that the distributed and decentralized optimization approaches are more suitable for its implementation compared to the centralized approach. However, the recent literature on P2P energy trading shows the usage of both the centralized and distributed optimization techniques like mixed-integer linear programming, nonlinear programming, and alternating direction method of multipliers.



(a) Centralized optimization



(b) Decentralized optimization



(c) Distributed optimization

Fig. 9. Different architectures for solving optimization problems.

4.3.1. Mixed-integer liner programming (MILP)

It allows the modeling of binary, integer, and real-valued variables in an optimization problem having a linear objective function and linear constraints [68]. In P2P energy trading frameworks, the binary variables usually arise in the home energy management stage where the prosumers aim to optimally schedule their local energy generation and storage devices for self-consumption and then find out the energy surplus or deficit to be traded in the local energy market. For instance, authors in [27] and [69] have proposed optimization models for the local energy communities in which each prosumer is equipped with the solar PV and Battery Energy Storage (BES) and has access to both the retailer and P2P trader to trade electricity with the grid and P2P market, respectively. The formulated algorithms provide optimal decisions about the BES charging and discharging $(P_{bes,n}^{ch}(t), P_{bes,n}^{dis}(t))$, quantum of electricity to be transacted with the grid $(P_{g,n}^{b}(t), P_{g,n}^{s}(t))$, and quantum of electricity to be transacted in the P2P market $(P_{p2p,n}^{b}(t), P_{p2p,n}^{s}(t))$; while considering the social welfare of prosumers and device operating constraints. Battery depreciation cost $(C_{bes,n}(t))$ and levelized cost of PV power $(C_{pv,n}(t))$ have also been incorporated in the objective function proposed in [27]. The generalized form of optimization problems proposed in [27] and [69] is as follows:

$$\min \sum_{n=1}^{N} \sum_{t=1}^{T} \left(C_{g,n}^{b}(t) + C_{p2p,n}^{b}(t) - C_{g,n}^{s} - C_{p2p,n}^{s}(t) + C_{bes,n} + C_{pv,n}(t) \right) \tag{7}$$

s.t. power balance constraint, BES state of charge constraint, BES power limits, Grid power limits, P2P trading, and pricing constraints. In (7), $C_{g,n}^{b}(t)$ and $C_{p2p,n}^{b}(t)$ represent the cost of purchasing power from the grid and P2P market in a time slot $t \in \{1,\ 2, \ldots,\ T\}$ for a prosumer $n \in N$. Similarly, $C_{g,n}^{s}(t)$ and $C_{p2p,n}^{s}(t)$ represent the revenue from selling power to the grid and in the P2P market, respectively.

Linearization or convexification of an optimization problem helps in converting an otherwise complex and non-convex problem into a convex MILP problem. For instance, authors in [29] have proposed a near-optimal algorithm named Energy Cost Optimization via Trade (ECO-Trade) to coordinate P2P energy trading among the smart homes in a microgrid. Bi-linear programming has been used to break down the non-convex MINLP problem into multiple MILP problems, and pareto optimality condition has been included to achieve fair cost distribution among the participants. The results have shown a reduction in the required computation time with minimal impact on the accuracy. In the same manner, the complex problem of achieving fair P2P electricity and heat trading between commercial and residential prosumers is linearized as an MILP problem through McCormick relaxation in [70]. McCormick envelopes transform the non-convex MINLP problem into a convex problem leading to reduced computational overhead [71]. In [18], the P2P trading mechanism is modeled as MILP by linearizing the non-linear and bilinear terms arising in the problem formulation. The objective of the algorithm was to maximize total revenue from solar PV power by optimally allocating the forecasted PV generation and uncertain PV power to the time flexible and power flexible loads of the consumers, respectively, in the P2P market. Thus, the objective function included the terms representing the income from selling forecasted PV power, income from selling positive PV generation deviation, gains from avoiding the compensation cost for negative power deviation, and payments made for availing the upward and downward regulating capacities from the flexible loads of consumers. Similarly, MILP is used to model the ancillary service provision framework through P2P energy trading in [64].

4.3.2. Nonlinear programming (NLP)

NLP, which involves nonlinear objective function and/or constraints, is used in [72] to reduce the overall system losses associated with the P2P energy sharing in DC microgrids. Both the power distribution and power electronic converter losses are incorporated, which leads to a nonlinear formulation. It was observed from the results that the converter losses have a substantive contribution to the losses, and hence it should not be avoided while formulating loss minimization problems for the distribution systems having power electronic-based DERs. Authors in [73] have also used constrained NLP to formulate the optimal sizing and energy sharing problem for BES in the P2P trading network. Two ownership structures, namely Energy Service Provider (ESP) owned and user-owned BES, were considered for P2P energy trading and compared with the user-owned peer-to-grid (P2G) energy trading. The user-owned structure resulted in a higher net present value compared to the ESP-owned model. Still, the ESP-owned model is beneficial in the sense that the users can buy electricity at lower prices without investing in a BES. Similarly, the constrained NLP was used in [26] to formulate an optimization algorithm with a rolling time horizon to minimize the energy cost of the P2P energy sharing communities by 30% compared to the traditional P2G energy trading. The resulted cost reduction can also be explained conceptually using Fig. 10, which shows that the energy trading with neighbors minimizes the amount of electricity traded with the grid, which in turn leads to reduced bills and increased revenue compared to the P2G energy trading (with the fair assumption that $\pi^s_{p2p} > \pi^s_g$ and $\pi^b_{p2p} < \pi^b_g$).

A convex quadratic model is used in [74] to define a P2P energy trading problem that considers DER uncertainty. The objective function is the social welfare of prosumers, which is quadratic in nature. The Jacobian matrix is used to linearize the nonlinear network constraints. The power balance equation is modified to include an uncertainty parameter, and the problem is restated as a Robust optimization problem. From the mathematical programming perspective, the whole problem remains a quadratic convex optimization problem to be addressed in the presence of the given uncertainty set. Authors of [75] have adopted the mixed-integer NLP to formulate a stochastic optimization framework for the resilient operation scheduling of the interconnected energy hubs capable of performing P2P energy trading. Uncertainty related to renewable energy sources was taken into account through the scenarios derived from the historical generation data. For more discussion on uncertainty handling in a P2P energy trading framework, the readers are encouraged to refer to [76–79].

4.3.3. Alternating direction method of multipliers (ADMM)

In distributed optimization techniques, ADMM is a popular choice among researchers due to its simple formulation and guaranteed convergence for convex problems [67]. The algorithm solves the convex optimization problems by breaking them down into smaller problems that are comparatively easier to handle than the original problem. For a decomposable problem (8) with the coupling constraint (9), the general formulation of ADMM is as follows [80]:

$$\min_{x,y} f(x) + g(y) \tag{8}$$

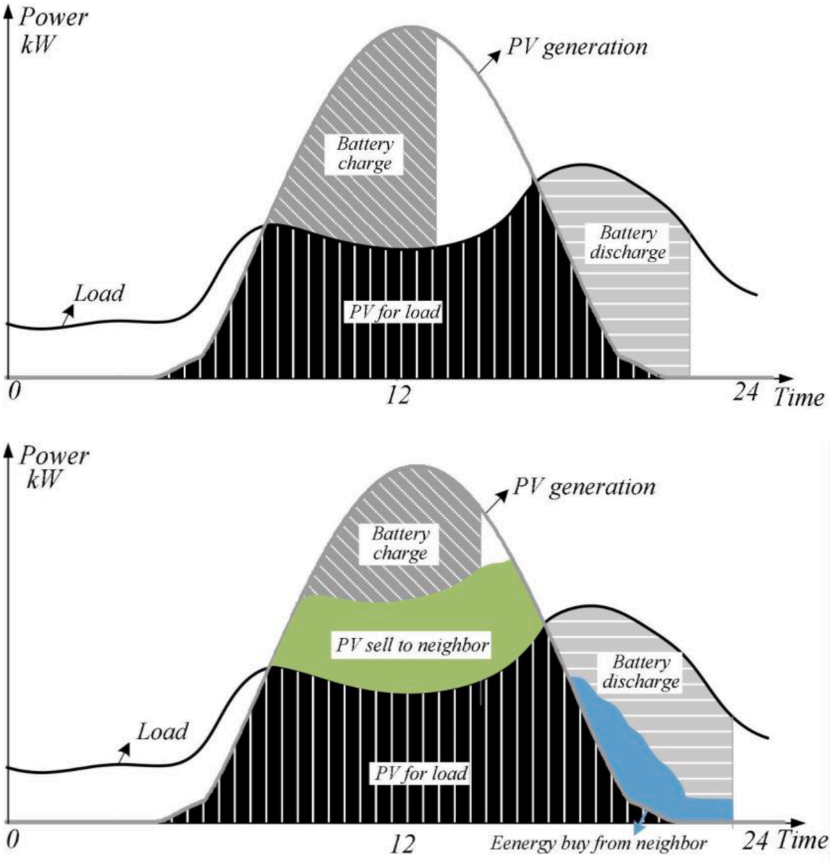


Fig. 10. Schematic of charging and discharging behavior of battery with PV generation (a) P2G energy trading, and (b) P2P energy trading [26].

$$s.t.\ Ax + By = C \tag{9}$$

where $x \in X$ and $y \in Y$ are variables, and A and B are given parameters. It can be observed that x and y are coupled through the equality constraint (9). The augmented Lagrangian function in the domain $\{x \in X; y \in Y\}$ can be defined as in (10).

$$L_\rho(x, y, z) = f(x) + g(y) + z^T(Ax + By - C) + \frac{\rho}{2}||Ax + By - C||_2^2 \tag{10}$$

where ρ is the Lagrangian dual variable which is also called penalty parameter. The standard ADMM algorithm updates the variables iteratively using (11), (12), and (13).

$$x^{k+1} \ := \ argmin_{x\in X}\ L_\rho\left(x, y^k, z^k\right) \tag{11}$$

$$y^{k+1} \ := \ argmin_{y\in Y}\ L_\rho\left(x^{k+1}, y, z^k\right) \tag{12}$$

$$z^{k+1} \ := \ z^k + \rho\left(Ax^{k+1} + By^{k+1} - C\right) \tag{13}$$

The algorithm stops when the magnitude of primal and dual residuals is below the thresholds as shown in (14) and (15), respectively.

$$\left|\left|Ax^k + By^k - C\right|\right|_2 \le \epsilon_{pri} \tag{14}$$

$$\left|\left|\rho A^T B\left(y^k - y^{k-1}\right)\right|\right|_2 \le \epsilon_{dual} \tag{15}$$

Within the context of P2P energy trading, authors in [50] have used ADMM to find the generalized Nash equilibrium of a noncooperative game used to derive the energy sharing profiles of energy buildings. Adaptive penalty parameter selection is used to improve the convergence of the standard ADMM algorithm. In the P2P energy sharing problem proposed in [81], ADMM was used to solve the social utility function of a community and a payment bargaining problem. Decision variables were classified into two blocks considering the fact that the convergence of the algorithm is guaranteed if it can be transformed into an equivalent two-block structure. Likewise, as summarized in Table 4, further application of ADMM to realize distributed P2P energy trading can be found in [76,82–84].

4.4. Blockchain

In P2P energy trading, prosumers and consumers with different generation and demand capacities participate from the different locations of the distribution network. There are also multiple small energy and financial transactions taking place between them, and that information should be stored on a secure and reliable database. Moreover, all the participants should have access to the database so that they can cross-verify the transactions and have trust in the trading system. It is difficult to achieve all the aforementioned traits if a centralized database system is used in the implementation of P2P energy trading. Blockchain technology is used to overcome these challenges of the centralized database system.

Blockchain is a distributed database system that uses a P2P network of computers to facilitate decentralization. The transaction data is packed in a block and linked to the previous blocks to make a chain of blocks, as shown in Fig. 11. The blocks are linked via the hash, which is an alphanumeric string generated with the help of cryptographic techniques like SHA256 [85]. The linking of blocks makes it almost impossible to temper with the data on a blockchain, which leads to immutability. Blockchain also provides transparency as the database is distributed among all the participating nodes to access. The consensus mechanisms like Proof of Work (PoW), Proof of Stake, and Proof of Authority are used to verify the transactions and blocks and to achieve consensus among the unknown participants [86]. In a nutshell, the use of a blockchain-based distributed database system can provide transparency, immutability, privacy, authenticity, and trust of the users in any system operating in a P2P fashion. Moreover, the smart contracts, which are the computer codes stored on the blockchain, adds an additional layer of functionality on top of the distributed ledger technology [87]. They remove the need for any intermediary to execute the contract, which results in reduced execution fees with seamless and secure execution.

Table 4
Summary of literature on ADMM for distributed P2P energy trading.

Ref.	Objective
[76]	Consensus ADMM method to eliminate the need for a central coordinator to update the dual variable in an uncertainty-aware joint P2P energy and reserve market
[82]	Distributed ADMM to improve the convergence rate and scalability of a gas-electricity management framework for the fuel cell combined heat and power equipped dwellings participating in a P2P electricity trading system
[83]	A novel decentralized ADMM approach to minimize the communication and computation burden at a central entity by solving the market clearing problem of P2P energy trading in parallel at all prosumers
[84]	Fast-ADMM to devise a privacy-preserving distributed dynamic pricing strategy for P2P transactive energy systems in the smart grid

To leverage the aforementioned benefits of the distributed ledger technology, an auction-based bidding mechanism is proposed in [38] to facilitate P2P energy trading in a Virtual Power Plant (VPP) framework using blockchain-based smart contracts. The VPP model consisted of consumers, prosumers, a BES, and a diesel generator. P2P energy trading coordinator and technical VPP were introduced to handle the financial and technical issues at the VPP level. The smart contract is used to operate the bidding mechanism and is deployed on the Ropsten network, which is a PoW based public test network [88]. It consisted of four modules, namely construction, bidding, withdrawal, and control, for seamless execution of the bidding process. The authors argue that the use of public instead of consortium blockchain network provides transparency and adaptability necessary for the specific application. Four cases were created based on the available generation, load demand, and status of the BES to evaluate the performance of the proposed framework. Average execution time, which is the time between a transaction request and its confirmation (indicated via state update), is observed for a different number of participating agents. To keep the system consistent, a duration of 50 s is recommended for allowing another request from the same participant.

Permissioned blockchain networks and crypto tokens are also being used in the implementation of P2P energy trading. For instance, authors in [16] have developed a decentralized platform titled ‘DeTrade’ for P2P energy trading using blockchain technology. The platform consisted of two layers, namely the market layer and the blockchain layer. In the market layer, an auction-based market mechanism was used along with the decentralized ant-colony optimization to clear the market while maximizing the social welfare of both the prosumers and consumers. The blockchain layer was realized using a permissioned blockchain known as Hyperledger Burrow, which uses the Tendermint Byzantine fault-tolerance consensus algorithm to achieve transaction finalization within seconds [89]. The use of permissioned blockchain has allowed avoiding the transaction execution fees which needs to be paid as gas fee in the public Ethereum blockchain. Gas measures the amount of computational effort required to execute a transaction on Ethereum Virtual Machine [90]. The smart contract deployed on the blockchain was used to store the market-clearing results and also to facilitate real-time financial settlements using ‘EuroTokens’ cryptocurrency. Table 5 shows the functions included in the smart contract, their visibility which can be public or private, and allowed participants to execute the functions. Note that the trusted third party is responsible for (a) minting EuroTokens for new participants joining the market and (b) converting the EuroTokens back to monetary values if the participants want to leave the market.

The location of participants with respect to each other in the distribution network and their reputation based on their past performance in delivering the committed energy can affect the prosumers’ decision-

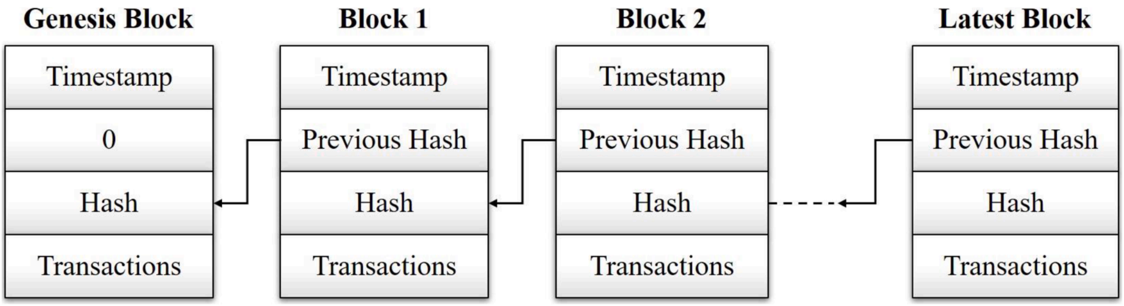


Fig. 11. Simplified representation of a blockchain database.

Table 5
Typical functions in a P2P energy trading smart contract.

Function name	Visibility	Accessibility
`registerHousehold`	Public	TTP
`isRegisteredHousehold`	Private	–
`mintEuroToken`	Public	TTP
`balanceOf`	Public	TTP + Smart agents
`initializeRoles`	Public	Smart agents
`storeClearingResults`	Public	Smart agents
`resetClearingResults`	Private	–
`validateAllClearingResults`	Private	–
`selectBestClearingResult`	Private	–
`getTotalPrice`	Public	Smart agents
`receivedEnergy`	Public	Smart agents
`redistributePoolFunds`	Private	Smart agents

making process in the P2P energy trading. A blockchain-enabled P2P trading framework is proposed in [91] to account for these factors in the trading mechanism without compromising the privacy of prosumers. Moreover, to reduce the memory footprint and enhance the scalability of the blockchain, a centralized database referred to as Advertise Database (AD) is used to record all the bids and offers that are referred to as Advertisement Transactions (ATs) in the paper. AD is managed by the grid operator, while the other participants have read-only access to achieve transparency. The blockchain only records the finalized trade details, energy injections, late fee details, price update information, and the dispute resolution smart contract. The results have shown that the combined computational, packet, and memory overhead to add a new block in the blockchain is 16 times more when ATs are stored in the blockchain compared to the case in which ATs are stored on AD. Thus, it can be concluded that only finalized information should be stored on the blockchain while other large chunks of data can be stored off-chain in traditional databases like AD to improve the scalability of blockchain-based P2P energy trading platforms.

From the aforementioned research work and the methodologies proposed in [31,39,40], and [92–103], it can be summarized that the applications of blockchain technology in P2P energy trading are not only limited to the distributed data storage. The cryptocurrency and smart contracts with blockchain as their underlying technology are also being utilized to fulfill different objectives. Table 6 categorizes [31,39,40], and [92–103] based on the purpose for which they have applied the blockchain technology in P2P energy trading. It can be observed that the majority of the referred research work has used the smart contract and cryptocurrency features of the blockchain technology instead of using it only as a distributed database.

Table 6
Summary of literature on blockchain technology.

Ref.	Use of blockchain
[39,92]	Just to realize a secure and transparent distributed database system
[31,93–95, 96,97]	To facilitate smooth and secure financial transactions using smart contract and/or cryptocurrency
[31,40,98,99,100,101, 97,102,103]	To implement distributed P2P market mechanisms using smart contract and/or consensus algorithms

5. Pilot projects

Peer-to-peer energy trading have certain challenges which can be addressed by conducting real-time pilot projects and regulatory sandboxes. Various projects are being pursued worldwide, and some of them are presented by the authors in [96,98]. A summary of few projects being implemented in a real-world environment is provided in Table 7 and some of them are briefly discussed in the following subsections.

5.1. *Brooklyn microgrid project*

Brooklyn MicroGrid (BMG) is a network of residential and commercial users in New York City (NYC) where the peer-to-peer trading of solar energy has been successfully demonstrated [109]. BMG project was started by LO3 energy to address the electricity reliability issues arising due to the outdated electrical grids in Brooklyn, NYC. The creation of a physical microgrid with significant amount of renewable generation allows the community members to reduce grid dependency by fulfilling their energy demand using the community generated power.

BMG marketplace provides a local energy trading platform using which the prosumers willing to sell excess solar power can connect with the consumers willing to purchase electricity generated from the green sources. It uses a Tendermint protocol based private blockchain called TransActive blockchain architecture. The conventional analogue meters are augmented with the smart meters called TransActive Grid meters capable of transferring the energy data to the blockchain. Fig. 12 depicts the installation of a TransActive Grid smart meter, with the TransActive Grid smart meter labelled ‘a,’ the distribution box labelled ‘b,’ the existing utility meter labelled ‘c,’ and the domestic fuse box labelled ‘d’ [110]. Trading on the BMG marketplace is usually done automatically using the Energy Management System (EMS) [9]. The participants only need to define preferences regarding the energy source and price limit in the mobile application for the EMS to conduct the P2P energy trading. A few screenshots of the BMG mobile application are provided in Fig. 13 [111].

5.2. *Pebbles project*

Pebbles stands for ‘Peer-to-peer energy trading based on blockchains’. It is a research project funded by the German Federal Ministry for Economic Affairs and Energy with Siemens, Allgäuer Überlandwerk (regional utility), AllgäuNetz (distribution system operator), and other project partners as the members of the consortium [112]. The project aims to realize decarbonization, decentralization, and digitization in the energy sector by developing a blockchain-based local energy trading platform. The developed platform will be implemented at the Wildpoldsried town in the Bavarian Allgäu region of Germany.

Table 7
Summary of P2P energy trading pilot projects.

Project name	Implementing nation	Observation	Developed infrastructure	Ref.
Piclo	United Kingdom	An online system for localized energy trading has been developed	A digital interface useful for prosumers to trade their energy	[104]
Vandebron	Netherland	Consumers can buy power from wind farms which is a kind of peer-to-peer energy trading	Online trading platform to enable efficient business	[105]
Peer Energy Cloud	Germany	The utility aims at developing a P2P trading mechanism to deal with the excess production of energy at a localized level	Digital infrastructure using IOT technology	[106]
Smart Watts	Germany	A cost-effective energy supply system that falls under the broad category of P2P energy trading is developed	Smart metering infrastructure using Internet of Energy	[105]
Yeloha and Mosaic	USA	The excess solar power in one apartment is sold out to other apartments that do not have rooftop solar installations	Project discontinued	[107]
Sonnen Community	Germany	The hybrid solar PV and battery system installed at different locations at the community level try to exchange power instead of pumping it to the grid	Digital applications that enable P2P trading	[107]
Lichtblick Swarm Energy	Germany	The swarm battery tries to optimize the usage of solar PV and the storage system by which the excess power can be sold	IT infrastructure for efficient utilization of resources	[108]
TransActive Grid	Brooklyn	The project enables consumers to buy or sell energy, as necessary	Blockchain interface with software and hardware layers	[105]
Prosumer Driven Integrated Smart Grid	India	A peer-to-peer energy trading testbed (PoC) consisting of three peers has been developed and demonstrated at IIT Gandhinagar	Physical, communication, and application layer integration through smart agent and blockchain technology	–

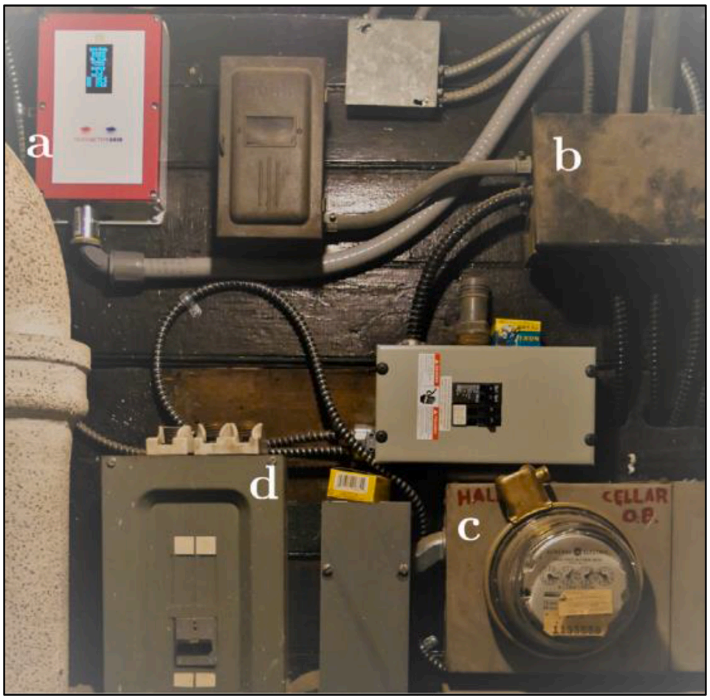


Fig. 12. Installation of a TransActive Grid smart meter [110].

The DERs at the site comprise solar panels and wind turbines, as shown in Fig. 14 [113]. Apart from the renewable generation sources, the developed platform also supports flexible power from BES and controllable loads such as heat pumps and EV charging stations. The prosumers with local generation sources use the developed platform to trade their electricity directly to the consumers without going through the intermediaries. On the other hand, consumers communicate their preferences for electricity purchase, such as the source and price for electricity. The platform is integrated with blockchain technology to seamlessly manage market transactions, enable transparency, and develop trust among the users. A dashboard depicting the real-time operational data of the local energy market developed by Pebbles is shown in Fig. 15 [112].

5.3. Blockchain-based P2P solar power trading pilot project in Uttar Pradesh, India

Uttar Pradesh was the first state in India and South Asia to implement a blockchain-based P2P solar power trading pilot project [114]. The Indian Smart Grid Forum (ISGF) led the initiative, with assistance from Power Ledger. ISGF is a Government of India public-private partnership program aimed at accelerating smart grid deployments throughout the country, whereas Power Ledger is an Australian technology company that develops software that allows users to track, trace, and exchange energy. Uttar Pradesh Power Corporation Limited (UPPCL) and the Uttar Pradesh New and Renewable Energy Development Agency (UPNEDA) hosted the project.

The pilot project included nine prosumers and three consumers from Lucknow to simulate P2P solar power trading. The prosumers were

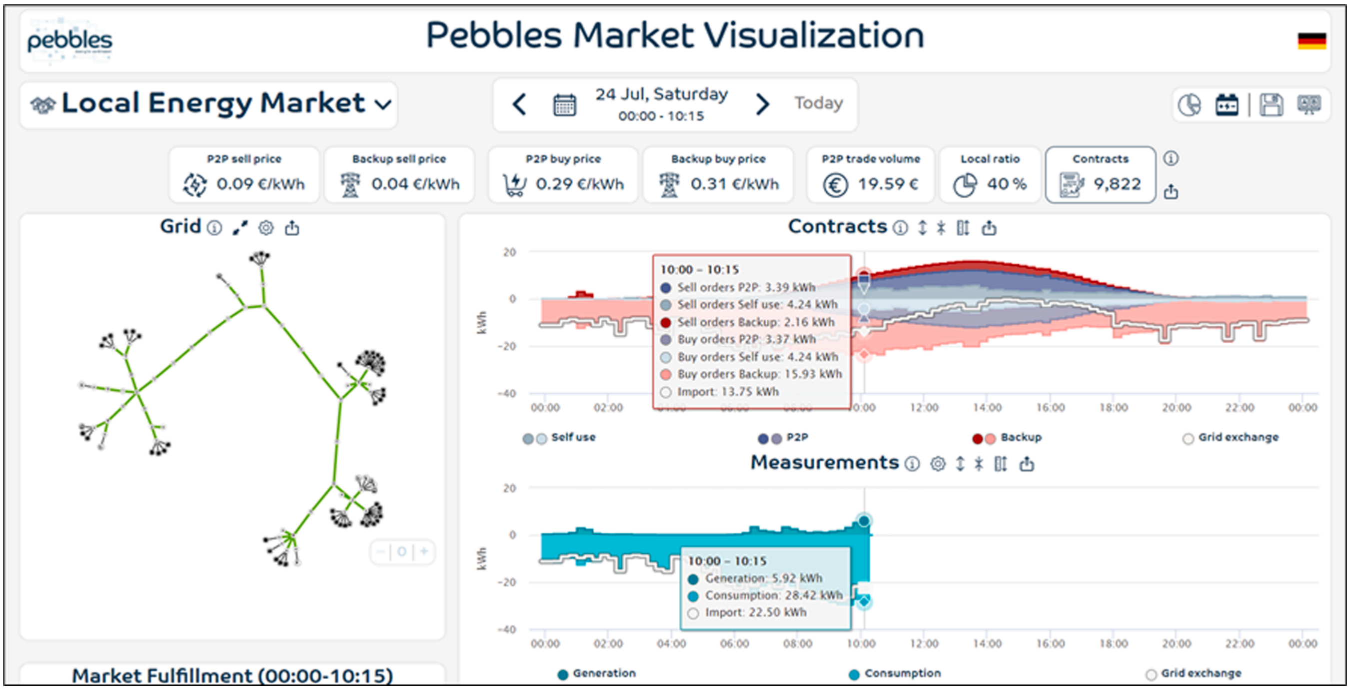
Switch on to purchase energy from the Microgrid.

Fig. 13. Screenshots of the BMG mobile app [111].

Fig. 14. Wind turbines and solar panels at Wildpoldsried [113].

having the rooftop solar PV systems installed on their buildings. One of the major requirements for implementing blockchain-based P2P energy trading from a technical standpoint is the availability of smart meters, communication infrastructure, and their integration with the blockchain-based trading platform. However, deploying blockchain technology was not a difficult task for the state utility because UPPCL had already replaced over 8,00,000 energy meters with smart meters in various cities, including Lucknow. Fig. 16 depicts a simple diagram showcasing the integration of smart meters with the blockchain platform, as highlighted in one of the reports submitted by Kanpur Electricity Supply Company Ltd. (KESCo) to UPPCL [115].

ISGF provided online training sessions to participants on various functions of the blockchain platform as well as the procedures that must be followed to engage in trading operations [116]. Since this was a pilot study, the participants engaged in three months of simulated trading with no monetary exchange. ISGF experimented with various trading logics and test scenarios that can benefit all stakeholders, including the utility, during this time. According to the Power Ledger, the pilot P2P market achieved a 43% lower price than the retail tariff. The results and recommendations of the pilot project were presented to UPPCL and the Uttar Pradesh Electricity Regulatory Commission (UPERC) for consideration in the drafting of state regulations to promote P2P energy trading. Following the successful completion of the pilot, UPERC issued a tariff order instructing all utilities in the state to take the pilot into its



24 Jul, Saturday
00:00 - 10:15

P2P sell price: 0.09 €/kWh
Backup sell price: 0.04 €/kWh
P2P buy price: 0.29 €/kWh
Backup buy price: 0.31 €/kWh
P2P trade volume: 19.59 €
Local ratio: 40 %
Contracts: 9,822

10:00 – 10:15
Sell orders P2P: 3.39 kWh
Sell orders Self use: 4.24 kWh
Sell orders Backup: 2.16 kWh
Buy orders P2P: 3.37 kWh
Buy orders Self use: 4.24 kWh
Buy orders Backup: 15.93 kWh
Import: 13.75 kWh

10:00 – 10:15
Generation: 5.92 kWh
Consumption: 28.42 kWh
Import: 22.50 kWh

Fig. 15. Local energy market dashboard developed by Pebbles [112].

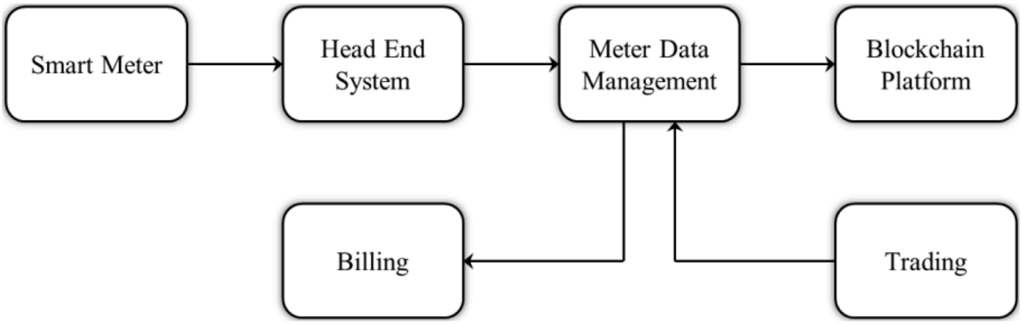


Fig. 16. Smart meter integration with blockchain by UPPCL.

next phase of integration with the existing billing system so that P2P solar power trading can be made operational in the state [13].

5.4. *P2P energy trading testbed at Indian Institute of Technology Gandhinagar, India*

An experimental testbed has been developed at the Indian Institute of Technology Gandhinagar (IITGN), Gujarat, India, to demonstrate the performance of P2P energy trading in the secondary LV distribution network. Figs. 17 and 18 depict, respectively, a schematic layout and the experimental setup that is being developed.

The testbed consists of three peers namely Peer A, Peer B, and Peer C. Peer A, as shown in Fig. 17 acts as a prosumer and has a 3.5 kWp rooftop solar PV system, a 7.5 kWh BESS, and around 2 kW in-house load. The BESS is used for in-house energy management via the hybrid inverter shown in Fig. 18. After meeting the in-house load demand, this peer can participate in peer-to-peer energy trading. Peer B also acts as a prosumer, with a connected load of around 1 kW and an EV that can operate in both the Vehicle-to-Grid (V2G) and Grid-to-Vehicle (G2V) modes. The EV under consideration is a three-wheeler campus cart powered by a 90 Ah, 51 V Lithium Ferrous Phosphate battery. This peer does not have a renewable energy source, but by operating the EV in V2G mode, it can sell power to other peers and participate in P2P trading. Peer C, the third peer, acts as a consumer with around 1.5 kW in-house load.

Fig. 19 depicts the integration of the hardware and software layers at the testbed. A blockchain-based web application demonstrated in [93] is used to facilitate peer-to-peer energy trading. The web application is integrated with the smart agent, which is shown using SA in Figs. 17 and 18. The smart agent is a microcomputer that receives load and solar PV generation data from energy meters. The received data is used in the forecasting and optimization modules of the smart agent. The web application allows the peers to float bids to buy or sell electricity in the P2P fashion. To access the application, each peer must first register for an account and complete the Know Your Consumer (KYC) registration by providing their user and energy asset information. They receive a digital wallet after successful registration, which can be used for financial transactions. On this developed testbed, the IITGN research team plans to integrate and test various P2P energy trading and demand response frameworks.

6. Future research directions

Peer-to-peer energy trading is one of the emerging and popular research areas in the field of smart power grids that is evident from the research works and real-world use cases discussed in Sections 4 and 5, respectively. The regulatory sandboxes and trial runs are being carried

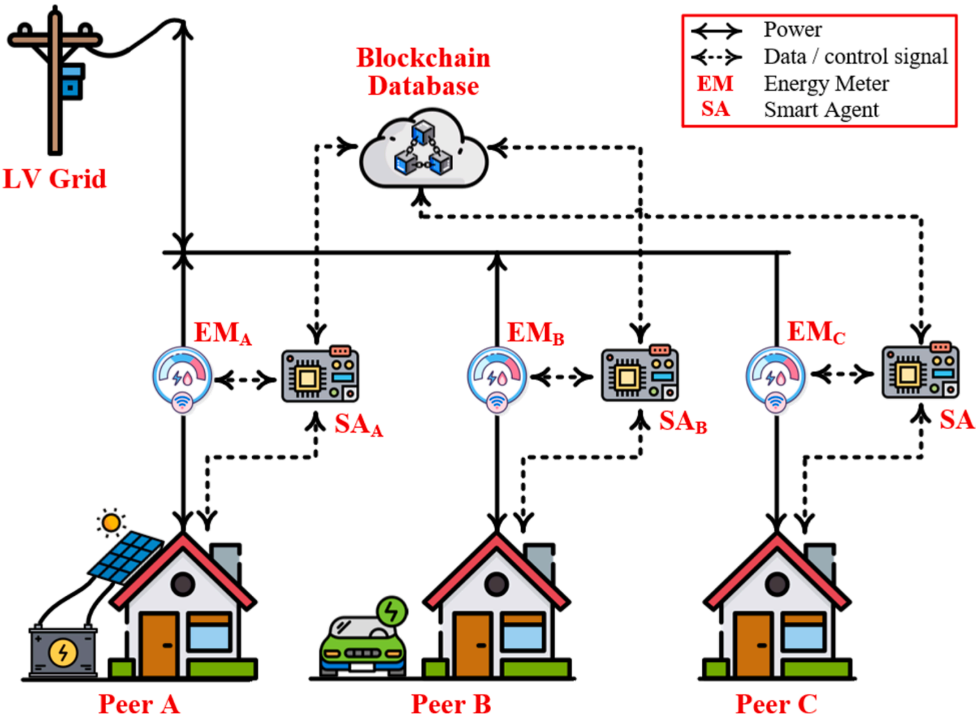


Fig. 17. Schematic layout of the P2P energy trading testbed.

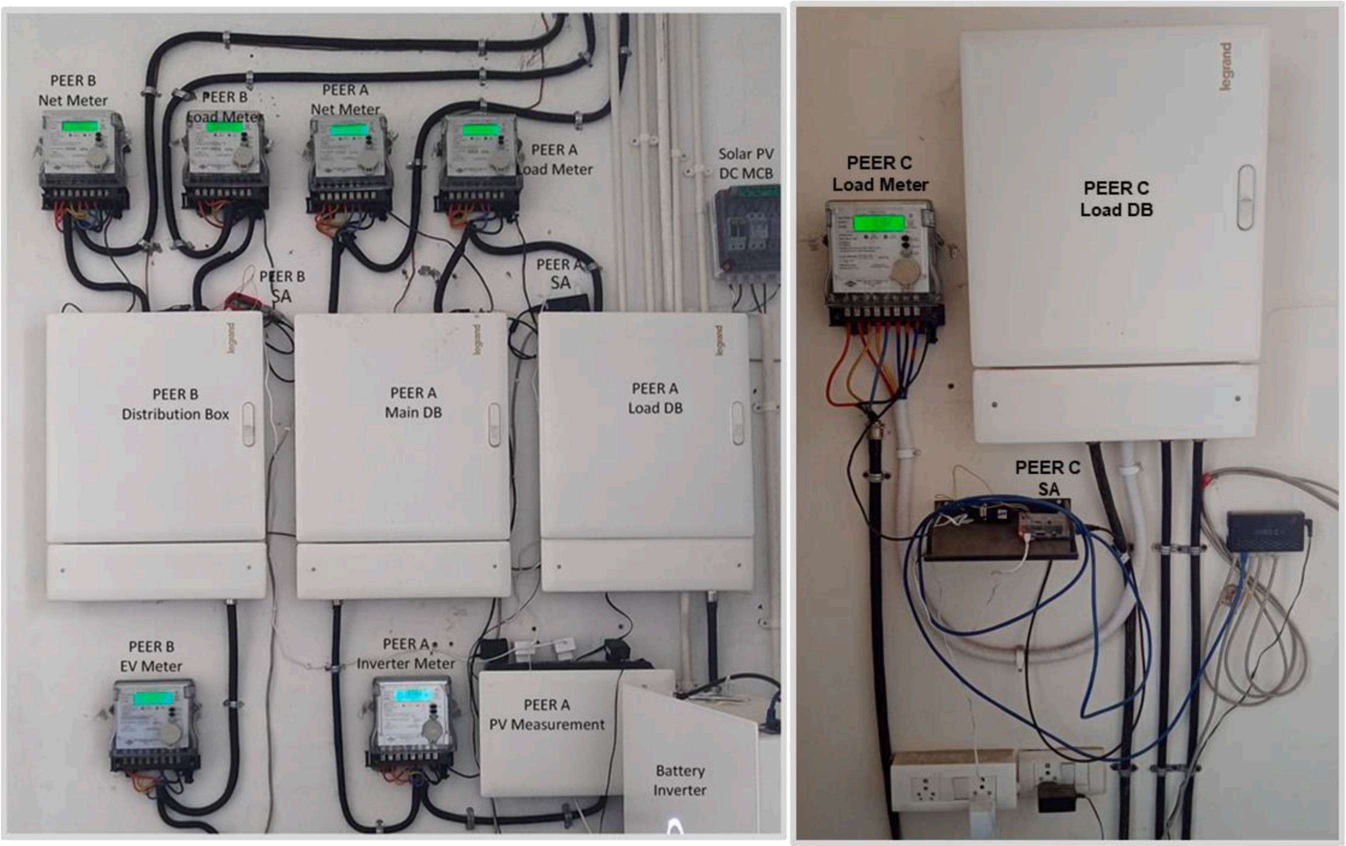


Fig. 18. P2P Energy Trading testbed at IITGN.

out to check the feasibility of this new energy sharing paradigm, while novel methodologies are being proposed by the researchers to extract its full potential. As applicable to the emerging concepts in any field, P2P energy trading frameworks proposed so far also need careful attention in some aspects to make them robust and practically realizable. Following are some of the aspects which the authors think should be considered in

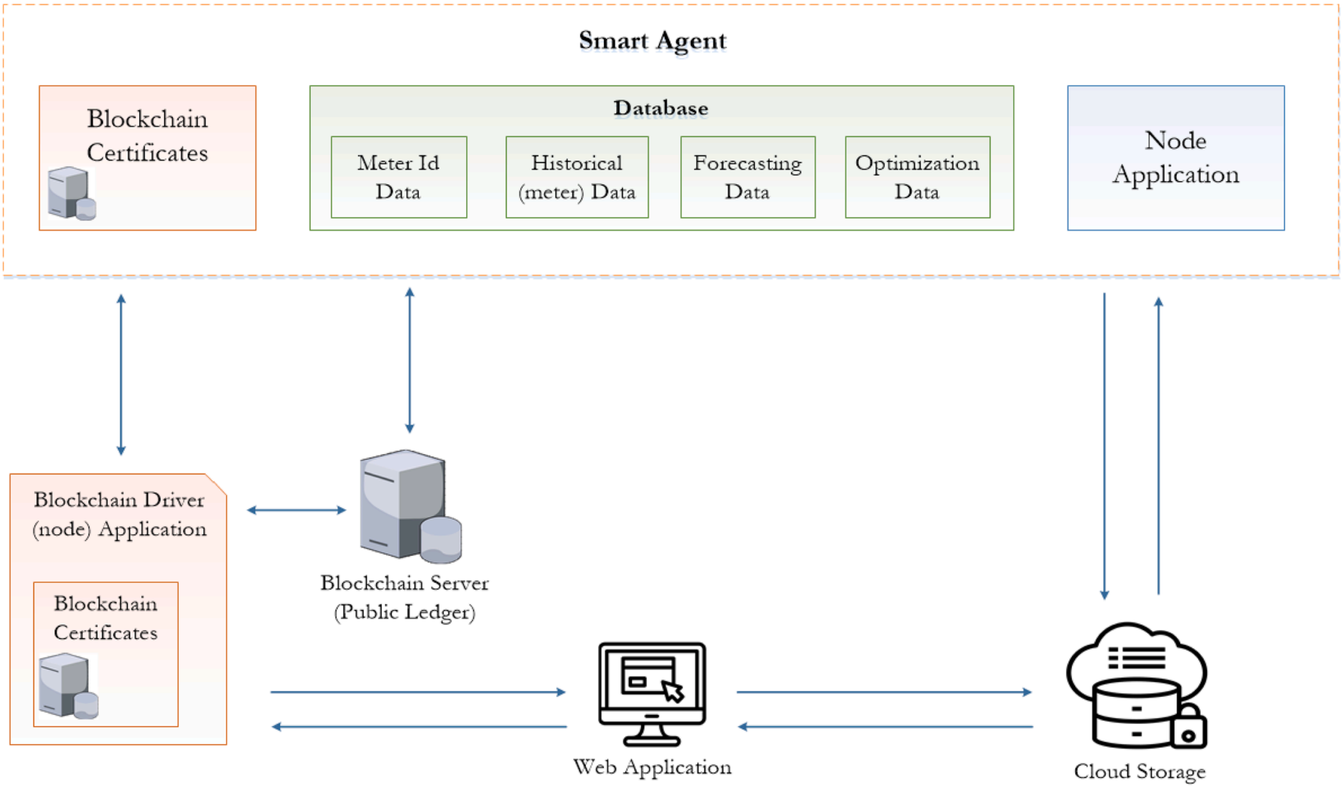


Fig. 19. Schematic representation of the hardware-software integration at the testbed.

the P2P energy trading frameworks:

6.1. Inclusion of network constraints

Owing to its economic benefits, the implementation of P2P energy trading can result in increased power injections and drawls at the nodes of the distribution network. If allowed without considering the network parameters, these energy transactions can lead to voltage fluctuations and line limit violations. For instance, Azim et al. in [19] had performed a simulation study of P2P energy trading on a 0.4 kV Danish LV distribution network and observed the over-voltage issues when multiple P2P trades were happening in a single feeder. It suggests that the network constraints should be given utmost importance while developing the P2P energy trading frameworks.

6.2. Financial viability of the utility companies

As P2P energy trading allows the end-users to fulfill their energy demands locally, the energy supplied by the utilities to the consumers reduces, which in turn can result in diminishing revenue streams for the utility companies. In other words, increased P2P energy transactions can raise the question about the financial viability of the utilities. The design of P2P energy trading frameworks should consider the role of a utility company with a sustainable business model without compromising much on its decentralized nature.

6.3. Technical viability of the base load power plants

Similar to the financial viability of the utility companies, the technical viability of the centralized base load power plants will also be affected due to increased local energy trades. The base load plants having a certain amount of ramp-up and ramp-down time and running to deliver a predefined amount of electricity may come across more fluctuating patterns of energy demand. In some time instances, it may happen that the energy generated from the power plants needs to be wasted as the original demands were already fulfilled locally, and it was quite expensive to completely shut down the units for short durations. Looking at the aforementioned scenarios, a synchronized operation between the centralized generating stations and local energy communities is required to maintain the stable operation of the centralized base load power plants.

6.4. Network usage charges and loss allocation

In P2P energy trading, the physical delivery of electricity is still happening via the distribution network corridors owned by the utility. Each peer is obligated to pay charges to the utility for utilizing these corridors. The collected charges can be later utilized by the utility companies to maintain or upgrade the network. Moreover, the power transfers through the network result in line losses, which should be compensated in a P2P fashion either via injecting an additional power equal to the losses from the peer or via including the cost proportional to the losses occurring during the power transfer. Hence, there is a need for an intelligent P2P pricing mechanism that can allocate the network usage and loss charges to each P2P trade based on the amount of energy transacted and the network corridors used to realize that energy transaction.

6.5. Customer participation and scalability

To reap the full benefits of P2P energy sharing platforms, more and more prosumers and consumers should be participating in the local energy trading. Now, customer participation in P2P trading is affected mainly by the level of motivation and the scalability of the platform. The P2P pricing mechanisms should be designed such that the participants at least gain something in comparison to the P2G trading. Also, multiple energy selling and buying options should be available to them, which can be made possible by designing a scalable P2P framework. A P2P energy trading platform can be called scalable if it can accommodate both the ever-increasing number of participants and associated energy and financial transactions without jeopardizing the stability of the platform.

6.6. Preserving the privacy of participants

In P2G energy trading, the information exchange happens between the trusted central entity and the customer. On the other hand, the exchanges of sensitive information happen multiple times between multiple peers who may or may not be knowing each other. Hence, it should be of utmost importance that the P2P energy trading platforms entrust participants about preserving their privacy. Failing to do so may lead to undesirable privacy breaches and can result in reduced participation of the customers in the P2P energy trading platforms.

7. Conclusion

Peer-to-Peer (P2P) energy trading is a new approach in the smart grid domain that enables the realization of local energy markets. By reviewing recently published papers on the subject, this paper aimed to provide researchers with a general understanding of the various concepts in P2P energy trading. With the aforementioned aim in mind, the structure of P2P energy trading has been discussed with the various layers involved. A typical architecture of a peer participating in P2P energy trading was presented, demonstrating the importance of a smart agent for efficient and seamless energy sharing. To understand the role of the various stakeholders, the generalized steps involved in the trading process have been highlighted. The recent literature on the topic has been classified and reviewed based on the approach used to formulate the P2P energy trading markets. The methodologies observed and commonly used by the researchers to develop the P2P energy trading frameworks included cooperative and noncooperative games, various auction mechanisms, mathematical optimization, and blockchain smart contracts. The paper also summarized the various P2P pilot projects that are taking place around the world to supplement the review of research work with real-world implementations. A brief discussion of the Brooklyn microgrid, Pebbles project, and P2P pilot from an Indian state was included, along with the authors' experiences with developing the P2P energy trading testbed at the Indian Institute of Technology Gandhinagar. Based on the research reviewed in this paper, it is feasible to conclude that P2P energy trading is still in its early stages. Various techno-socioeconomic challenges identified in this article should be addressed, and appropriate regulations should be drafted for successful realization of P2P energy trading in smart distribution networks.

Declaration of Competing Interest

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

Data Availability

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

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