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Peer-to-peer energy trading: A review of the literature

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ABSTRACT

Distributed energy resources have increased considerably in the United States and the world in the last decade. The proliferation of prosumers generates the opportunity to have a more decentralized and open energy market. Given this opportunity, the Peer-to-Peer (P2P) trading energy paradigm appears, where consumers and prosumers can exchange energy without the need for an intermediary. Because P2P energy trading plays a fundamental role in the proliferation of renewable energies and the system flexibility for a low-carbon energy transition, this paper provides a review of the P2P energy trading that is necessary to understand the current approaches, challenges, and future research that should be conducted in this area. As a result, areas for consideration were identified and grouped into the following six topics: (1) trading platform, (2) blockchain, (3) game theory, (4) simulation, (5) optimization, and (6) algorithms. The study concludes by identifying several challenges that may give way to future research, such as integrating generation, transmission, and distribution into studies, large-scale studies, and modeling of consumer and prosumer complex behavior. Given P2P energy trading is a relatively new topic, there is still much work to be done to successfully implement the real-world model.

1. Introduction

The proliferation of distributed energy resources (DER) has dramatically changed how energy is produced, delivered, and consumed in the energy pipeline, including microgrids. The massive increase in prosumers, who both produce and consume energy, provides a more decentralized and open electrical network [1]. Furthermore, energy operators are no longer solely responsible for selling energy, but also for renting transmission lines so that prosumers can inject energy into the grid through the net metering programs. Currently, there are 70 countries in the world with mandatory net metering policies. Yet, some regional locations within a country, like Michigan (United States), Uttar Pradesh (India), and Saskatchewan (Canada), have decided to end the net metering policy to implement new distributed generation programs. The problem is that if more countries or states start to end net metering programs, the incentive to install photovoltaic (PV) systems or other types of renewable energy systems, like wind power or micro-hydro systems, will likely decrease. Additionally, the return on investment of current and future owners of renewable energy systems will likely decrease, which will impact the energy market and will cause a ripple effect in other complementary areas throughout society.

For a low-carbon energy transition, an increase in the generation of renewable energy is essential. For that reason, it is essential that new ways of compensation can be found for residential energy prosumers [2,3]. Due to the large growing number of DERs, it is an issue that potentially creates a relevant impact on the energy market. The increase in renewable energy at the residential level requires new market approaches to set prices, decentralize, and make flexible the energy market and the governance of the energy infrastructure [4]. It is necessary to create local energy markets where renewable energy generation can be traded locally without intermediaries' needs, directly between prosumers and consumers [5].

In recent years, Peer-to-Peer (P2P) trading has emerged as the alternative for prosumers to participate in the energy market actively. P2P allows prosumers to trade excess energy production with their peers and increase their benefits and consumer benefit. Also, P2P energy trading gives more flexibility to end-users, giving more opportunities to consume clean energy, and help transition to a low-carbon energy system. Additionally, the other actors in the electricity market can obtain benefits, such as reducing the peak demand for electricity, reducing maintenance and operation costs, and improving the reliability of the electrical system [6–8].

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There is a wealth of previous work reported in the literature regarding energy trading between prosumers and energy companies. The recent increase of DERs and energy prosumers is creating an impact on the energy market. According to Zhang et al. [6], P2P energy trading will improve the local balance of energy generation and consumption due to the greater diversity of energy generators. It also allows for the decentralization of the energy market [5]. Centralized operations are highly vulnerable to supply chain interruptions. Currently, the energy system is immensely centralized in a few generations, transmission, and distribution companies. In particular, by reducing the energy system's centralization, the P2P model helps to reduce the risk of failure of the energy network. In the face of cyberattacks or natural disasters, the P2P model will allow the continuous power supply for the consumers who are physically close to a prosumer. Therefore, a literature review on P2P trading energy is needed to understand better the challenges, opportunities, and directions that future research should take.

This paper aims to summarize insights of recent P2P energy trading academic studies, highlight the research challenges, and recommend future research opportunities for P2P energy trading.

2. Peer-to-peer literature review

2.1. Overview of net metering policies

Although distributed renewable generation represents only 1% of global electricity generation, it has increased in recent years, representing new challenges and opportunities [9]. The foremost opportunity is to reduce dependence on the grid by installing renewable generation systems for electricity generation. In return, more individual consumers and companies are moving towards energy self-generation. Some policies, programs, and regulations that promote the installation and use of renewable energy to increase distributed generation are solar mandates, net metering, and feed-in pricing, as well as measures that encourage community aggregation and policies that promote utility activities and investment [10]. Last year California became the first state in the United States to make PV systems mandatory in most new homes; this new solar mandate came into effect in 2020. New York City also implemented a solar mandate for new buildings and particular construction renovations [10].

At the beginning of 2020, 70 countries had net metering policies at the national level (see Fig. 1); while other countries, such as the United States and Canada, have net metering policies at the state level. The net metering policies compensate renewable energy generation owners for the surplus electricity that enters the grid. In the last year, there have also been some changes in net measurement policies. In Uttar Pradesh (India), Michigan (United States), and Saskatchewan (Canada), net metering policies were canceled. Also, in the United States, Louisiana's state reduced the amount paid to homeowners for photovoltaic solar energy [10–12].

Virtual Net Metering (VNM) is a bill crediting system for community renewable energy facilities. The energy produced in the system is shared between various users so that several users can receive credits on their electricity bill for excess energy production. Policies in support of VNM have increased in recent years. In 2019, Spain approved a regulation that allows multiple users to be associated with a single renewable generation system. In New Delhi, India, the net metering policy for PV systems was expanded to include VNM. In the United States, at least 16 states have regulations that support the VNM. Additionally, in New Mexico, a law was approved that allows the development of solar community projects [10,11,13].

2.2. Overview of peer-to-peer energy trading

In recent years, the increase in distributed energy resources has changed the energy distribution systems. Simultaneously, how energy is produced and consumed is changing dramatically, and traditional energy consumers are becoming prosumers [14]. The generation of electricity by prosumers is intermittent and difficult to predict, as it is highly influenced by the quantity of sunshine and temperature (which is constantly changing). When prosumers have an electrical energy surplus, there are several options. The energy can be stored in a storage device for later use, it can be exported to the electricity grid, or the excess electricity can be sold to other energy consumers. Direct energy trade between consumers and prosumers is called the P2P energy trade.

Fig. 2 shows a schematic of the P2P energy trading model. The model comprises four main actors: consumers, prosumers, electric company,

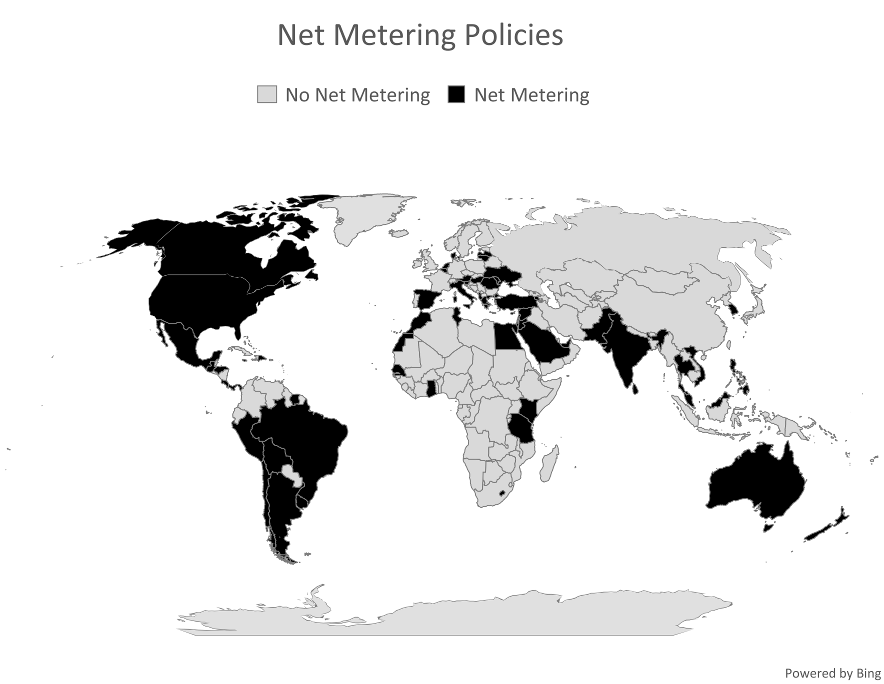

Fig. 1. Countries with net metering policies.

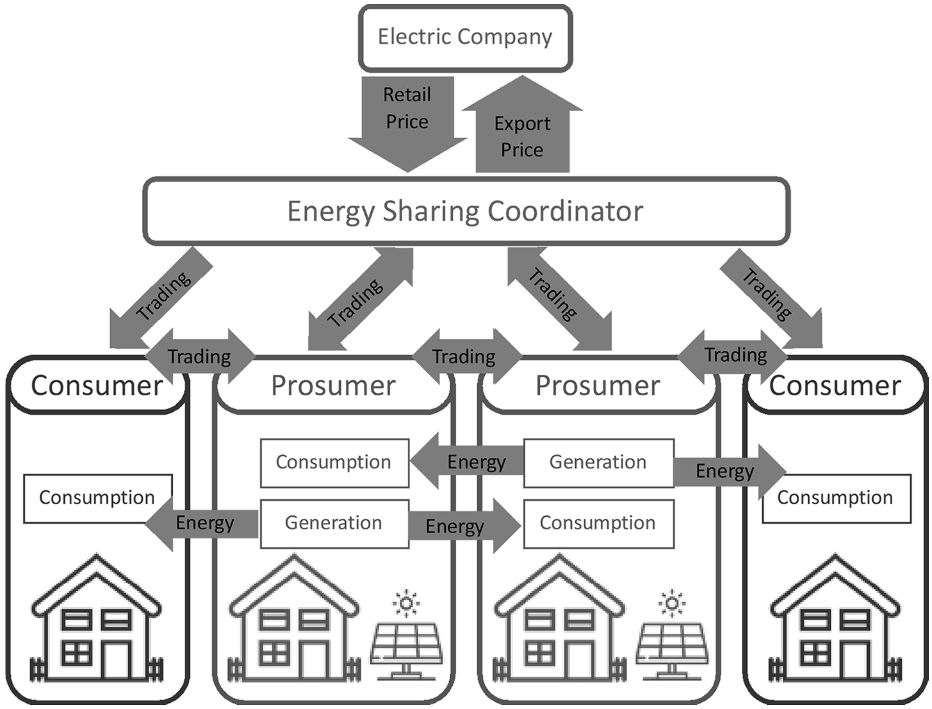

Fig. 2. P2P energy trading model [15].

and energy sharing coordinator. The difference between prosumers and consumers is that prosumers generate and consume electricity, and consumers only consume. Between prosumers and consumers, there is an exchange of energy and money represented by the trading arrows and the energy arrows. A prosumer can sell electricity to a consumer or to another prosumer. The entire negotiation process is carried out using a platform that functions as an energy exchange coordinator. The trading arrows in one direction represent that consumers can only receive energy from the energy sharing coordinator. The bidirectional trading arrows represent that prosumers can buy and sell electricity to the energy sharing coordinator [15–17].

The concept of P2P is also known as a shared economy, and it is typically implemented in a local grid system [18]. P2P energy trading involves a group of participants, including generators, consumers, and prosumers. Peers buy or sell energy directly from each other without intermediating conventional energy suppliers. The energy export price is set below the retail price to encourage the prosumers to balance the distributed generation. In this way, prosumers are encouraged to directly share their surplus energy with their neighbors to obtain more significant benefits. In the P2P energy model, prosumers and consumers first share their generation and consumption in a local market at a domestic price and then trade with a retailer. The domestic price is generally set between the export price and the retail price. Thus, prosumers or consumers, regardless of whether they are sellers or buyers of electricity, benefit from P2P energy exchange.

Conventional energy trading is mainly one-way. Electricity is typically transmitted from large-scale generators to consumers over long distances, while cash flow is the other way around. In contrast, P2P energy trading encourages multi-directional trading within a local geographic area, as is shown in Fig. 2. In this way, the massive increase in energy prosumers provides a more decentralized and open electrical network [1]. The increase in renewable energy at the residential level requires new market approaches to set prices and decentralize the energy market and the governance of the energy infrastructure [4]. It is necessary to create local energy markets where renewable energy generation can be traded locally without intermediaries' needs, directly between prosumers and consumers [5]. A microgrid formed by prosumers and consumers exchanges energy with the electricity company. The exchange is done through the energy sharing coordinator. Global energy surpluses in the microgrid can be traded to the electricity company at an export price. Furthermore, the extra electricity demand is supplied by the electricity company at a retail price [15,16]. According to Zhang et al. [6], P2P energy trading will improve the local balance of energy generation and consumption due to the greater diversity of energy generators.

The implementation of the P2P model will have some impacts on the community. An effect on lifestyle and cultural practices about the supply and demand for electricity will be created. Simultaneously, local training and job opportunities will be generated for the administration and maintenance of P2P systems. Additionally, a greater social trust will be generated, improving transparency in transactions, and reducing fraudulent transactions. Ultimately, a greater attachment to the community will be created as the participants have a more direct connection with each other, thus increasing a sense of attachment to that community. They must coordinate with each other to maximize profits [19,20]. Because of these benefits and more, several projects worldwide have focused on P2P energy trading. Notable examples are Piclo in the UK, Vandebron in the Netherlands, sonnenCommunity in Germany, and Yeloha and TransActive Grid in the United States [5,6,15,21,22]. Table 1 provides a summary of P2P trading energy projects including their primary outcomes.

2.3. Current approaches and opportunities

After analyzing several papers published in recent years on P2P energy trading, it was found that the approaches most used in articles converged to six main areas, which are explored in the following sections of this document. The first area is trading platforms (Section 2.2.1), the second is blockchain (Section 2.2.2), the third area is game theory (Section 2.2.3), the fourth is simulation (Section 2.2.4), the fifth area is optimization (Section 2.2.5), and the last one is algorithms (Section 2.2.6).

Table 2 summarizes the main studies carried out on P2P energy trading and is organized into the six areas mentioned above; as can be

Table 1
. *Projects of P2P trading energy* [20,21,23].

Project Name	Country	Year	Outcomes
Community First Village	United States	2015	Build a self-sustained community for homeless
Electron	United Kingdom	2016	P2P trading platform
EMPOWER	Norway, Switzerland, Spain, Malta, and Germany	2015	Architecture and ICT solution in the local market
Enerchain	Europe	2017	P2P trading platform
Energy Collective	Denmark	2016	Local P2P market in Denmark
Lichtblick Swarm Energy	Germany	2010	Plenty of services provided by energy supplier
NGRcoin	Belgium and Spain	2013	P2P trading platform
NOBEL	Germany, Spain, Greece, and Sweden	2012	ICT for energy brokerage system
P2P-SmartTest	Finland, UK, Spain, and Belgium	2015	Advanced control and ICT for P2P
P2P3M	The United Kingdom and South Korea	2016	Prototype od P2P trading platform
PeerEnergyCloud	Germany	2012	Cloud-based energy trading
Piclo	United Kingdom	2014	P2P trading platform
Smart Watts	Germany	2011	ICT to control consumption
SonnenCommunity	Germany	2015	P2P trading platform
TransActive Grid	United States	2015	Automatic energy trading platform
Vandebron	Netherland	2014	P2P trading platform
Yeloha, Mosaic	United States	2015	Terminated due to funding issues
Micro-Grid Sandbox	United States	2016	P2P trading platform using blockchain

Table 2
Current approaches in P2P trading energy.

Areas	Articles
Trading Platform	[6,7,24–36]
Blockchain	[27–32,34,36–41]
Game Theory	[6,33,39,40,42–50]
Simulation	[6,27,30–34,38–41,43,44,46–55]
Optimization	[6,24,27,31,34–37,40,42,45–47,50–57]
Algorithms	[24–27,30–32,34–42,46,47,49–53,56,57]

seen from the table, each of the studies generally involves more than one of the areas. Fig. 3 shows the details of the studies analyzed and the areas that each one involves. There are no articles that include all six areas, but there are four studies where five of the approaches were used. The studies include algorithms, optimization, simulation, blockchain, and trading platform or game theory. Additionally, eight of the papers involved four areas, 11 of the studies using three approaches, and most of the articles, 12 in total, used only two areas. It is important to note that in some studies where game theory and simulation are used, algorithms are also used to converge simulations and optimize game equilibrium. At the same time, trading platforms, particularly blockchain, use algorithms to optimize processes when carrying out energy transactions. Furthermore, some studies focused on trading platforms and blockchain use simulation to test operations. Moreover, when evaluating the energy exchange process, users' behavior, through the use of game theory, is also considered.

2.3.1. *Trading platform and blockchain*

An energy buying and selling platform allows storing all the information related to production, consumption, and contractual relations between the participants. Traditionally, when a digital transaction is made, it has to be validated by a central entity. Furthermore, it is in this intermediary that we place the trust and security of the operation. Currently, energy exchange platforms are being investigated not only in the traditional way, where one depends on an intermediary, but where one does not need a central entity. The P2P trading energy platforms are an important area for the massification of the P2P model. Reliable and secure platforms are necessary for users and the model. The studies on P2P trading energy platforms have been based mainly on platform architectures and on testing security and scalability. Zhang and colleagues [6] designed a P2P energy exchange platform and simulated P2P energy exchange using game theory. The authors proposed a hierarchical system architecture model to identify and classify the principal elements and technologies involved in the P2P energy trade. Test results on a low voltage microgrid show that P2P energy trading can improve the local balance of energy generation and energy consumption. Morstyn and McCulloch [24] propose a P2P energy market platform based on the new concept of multi-class energy management, to coordinate trade between prosumers with heterogeneous preferences, beyond purely financial. The multi-class energy management problem's decomposable structure is exploited to devise a distributed, price-driven optimization mechanism that provides scalability and privacy for prosumer data. Inam and colleagues [25] propose a new electricity exchange concept between

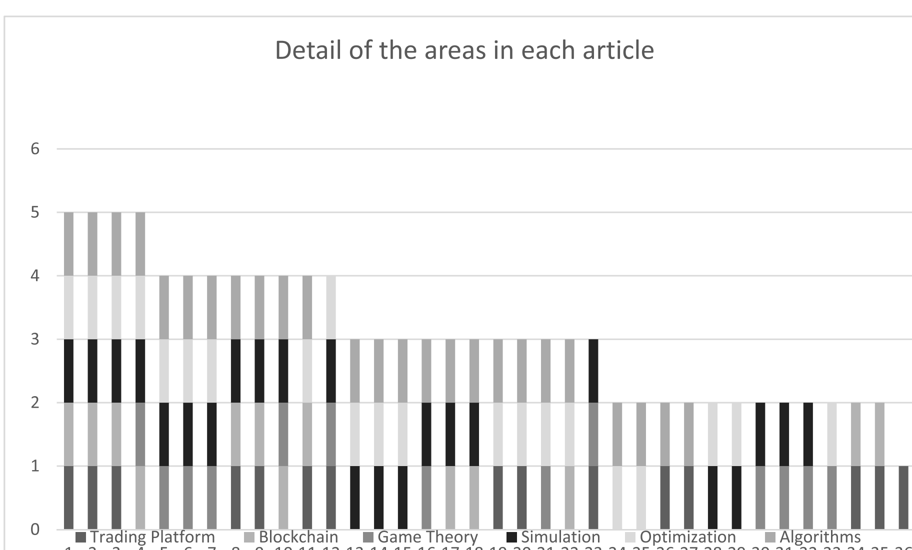

Fig. 3. Detail of the contribution areas in each article of P2P.

peers that creates an electricity market. These resource sharing microgrids provide affordable electricity and are powered by a Power Management Unit. Compared to conventional microgrids, this system requires less capital and is more scalable because it is built from the bottom up rather than relying on a large, centralized generation facility. Additionally, by managing aggregate demand, resources can be used optimally, further reducing generation and storage costs. Other studies propose a network of P2P homes with low-cost digital electricity meters, which allow optimization of energy consumption [26]. In other words, this platform is not based only on the exchange of energy but on the application of energy efficiency. Operating those devices on a P2P network enables a much more comprehensive range of energy-efficient applications and value-added services for the network. The proposed smart metering infrastructure consists of standard hardware and the existing communication infrastructure. Morstyn and colleagues [7] propose the concept of a federated power plant, a virtual power plant formed through P2P transactions between self-organized prosumers on a platform. This addresses the social, institutional, and economic issues facing top-down strategies for coordinating virtual power plants while unlocking additional P2P power trading value.

2.3.2. Blockchain

Blockchain is an innovative technology designed to increase security and decentralize transactions. Blockchain technology is a type of distributed database that can securely host critical information such as contracts, data, events, and monetary transactions. Critical data are stored in blocks and linked with chain [27]. In the last years, blockchain has been involved in the energy industry in various ways: scientific articles, pilot projects, business models, among others. Andoni and colleagues [28] identified more than 140 research and projects linking blockchain to the energy industry. The initiatives have been grouped into eight large groups: 1) metering/billing and security; 2) cryptocurrencies, tokens, and investment; 3) decentralized energy trading; 4) green certificates and carbon trading; 5) grid management; 6) IoT, smart devices, automation and asset management; 7) electric e-mobility; and 8) general-purpose initiatives and consortia [28]. Blockchain technology related to energy trading models is a new field. Existing research focuses primarily on decentralizing energy resources, security, and scalability of the blockchain network using the Internet, optimization, and new architectures for blockchain models.

Vangulick et al. [29] propose a blockchain technology for P2P trading energy, where the authors evaluate various designs based on criteria such as market acceptance, precision, privacy, security, and traceability. The proposed model is based on a consensus of Proof of Work instead of Proof of Stake, which generates a lack of synchronization to complete the transactions. Security is one of the essential issues when making energy transactions without depending on third parties. The study of Aitzhan and Svetinovic [30] has focused on testing the security and performance of a P2P platform for trading energy based on the blockchain through the simulation of scenarios. The developed system allows trading and negotiating the price of energy transactions anonymously. Mengelkamp and colleagues [5] present a local energy market's design and simulation using 100 residential prosumers and consumers. The model presented by the authors is based on blockchain technology and allows prosumers and consumers to exchange energy without the need for a central intermediary. Other studies have focused on how to decentralize power flow using blockchain. In this way, it is possible to program a mixture of charge from batteries and different energy resources from a microgrid. Additionally, there has been a focus on receiving fair payment for the energy transaction [31].

Other authors have used existing and validated blockchain platforms such as Ethereum and Consortium. Sabounchi and Wei [34] developed a P2P platform using Ethereum Blockchain. The proposed model was based on a contract theory for designing smart contracts that allow creating real-time contracts in the energy market. The smart contracts required a minimal need for third-party supervision. In the study, simulations were run to evaluate the model. Li et al. [40] used the Consortium blockchain for P2P energy trading. The model proposed by Li and colleagues establishes a credit-based payment scheme to reduce the delays generated by the confirmation of transactions. The system allows a fast and safe energy exchange. Besides, the authors propose a pricing system using the Stackelberg game for credit-based loans [40].

Another way to use blockchain for P2P energy trading is to trade energy between hybrid electric vehicles. The model proposes to use hybrid electric cars to be able to discharge and balance local energy networks. The designed model also uses a double auction mechanism to achieve the electricity price and the quantity of electricity to be exchanged [37]. The use of blockchain in microgrids is not limited to economic applications. Silvestre and colleagues [38] study is based on the tracking and attribution of energy losses during energy transactions where the expected power flows in the transactions do not match with the real operations. The study of Thakur and colleagues [39] used blockchain in the context of P2P energy trading for an energy auction platform. Using this platform, the authors demonstrated that the auction converges quickly, being an efficient system that also minimizes the loss of energy that can add commercial restrictions in the auction. Some studies using blockchain and P2P energy trading have focused on the platform's architecture and the different layers that the models should have [27]. Cali and Fifield [27] propose a seven-layer architecture model for energy transactions using blockchain. The proposed layers are as follows: energy policy and regulatory; business; power markets and pricing layer; control and optimization layer; information and data; communication; and power systems.

2.3.3. Simulation

Simulation is a numerical technique to perform experiments about a process or a system [58]. Some studies have used simulation tools to validate game theory models or P2P energy trading mechanisms. Simulation is a tool widely used in P2P trading energy studies, since being a model that is not yet fully working in the real world, it is necessary to test new mechanisms without a high cost. Additionally, using simulations tools, different models, and mechanisms can be compared. Wu et al. [51] use simulation to validate their proposed method of pricing strategies. The authors propose two user-centric pricing strategies for conducting P2P energy trading on microgrids: (1) the unified pricing strategy and (2) the identified pricing strategy. The unified price strategy consists of a centralized market group that determines the market-clearing price in a regular time interval. In contrast, the identified price strategy identifies each energy transaction at different times according to consumer supply. Hayes and colleagues [32] propose a co-simulation methodology that includes P2P energy platforms and energy distribution networks. The impact of the large-scale use of a P2P model and the potential benefits and impacts on the energy network can be evaluated using co-simulation. As a result, it is suggested that moderate utilization of P2P energy trading does not generate a significant effect on the grid.

Other researchers have used an existing platform for P2P energy trading, called Elecbay, to run simulations using game theory. The test results show that the P2P energy trade is capable of balancing local generation and demand. Therefore, it has the potential to allow a massive penetration of renewable energies in the electricity grid [33].

2.3.4. Game theory

Game theory is an area of applied mathematics that uses models to study interactions in formalized incentive structures called games. In P2P energy trading, researchers have widely used game theory to model the behavior of participants. Tushar and colleagues [42] provide an overview of using the game's theoretical approaches to P2P energy trading as a feasible and effective means of energy management. The authors discuss various games and theoretical auction approaches following a systematic classification to provide information on game theory's importance for smart energy research. Other studies aiming to find mechanisms to encourage the sustainable and beneficial participation of prosumers in the P2P models have used game theory in a motivational psychology framework [43]. Tushar and colleagues [43] developed a motivation psychology framework, which consists of a series of motivation models that a prosumer must satisfy before being convinced to participate in the energy trade. The authors have developed a game theory scheme to demonstrate that the coalition between different prosumers is stable. Through numerical analysis, Tushar and colleagues [43] have shown that carbon emissions can be significantly reduced compared to traditional schemes. Other studies have focused on using a canonical coalition game and motivational psychology models to propose a P2P energy exchange scheme [44]. The mid-market rate is used as a proposed P2P trade pricing mechanism to confirm the coalition's stability and guarantee the benefit to the prosumers to form a social coalition. As a result, they have obtained a consumer-centered scheme and has the potential to corroborate the prosumer's sustainable participation in the P2P energy trade [44]. Jing et al. [45] propose a P2P model for electricity and heating trade that allows the use of multiple energy storage technologies. The optimization of the model is based on a Nash non-cooperative game with guaranteed trading fairness.

Long et al. [46] proposed a P2P negotiation mechanism and modeled the decision-making process using game theory and Shapley value. The use of game theory delivered distributed energy management solutions for individuals in the negotiation process. Compared to other algorithms for P2P energy trading, the Shapley value trading mechanism, such as bill sharing, mid-market rate, and supply–demand ratio. The simulation results illustrate the effectiveness of the proposed method by significantly improving equity for P2P energy trading. Some authors investigate sustainable energy management focusing on a group of energy buildings with distributed transactions [47]. The authors present a two-stage energy exchange strategy. In the first stage, the total cost of social energy is minimized by finding the optimal profiles for sharing energy in a distributed manner. In the second stage, energy sharing is modeled as a non-cooperative game, and the existence of game equilibrium is illustrated. A relaxation-based algorithm is introduced to seek balance. The simulation results show that the proposed energy exchange strategy is economically beneficial for energy buildings and computationally efficient [47]. Wang and colleagues [48] present a P2P energy exchange mechanism through non-cooperative bidding between microgrids. Under a parallel, blockchain-based trading framework, the authors' proposed multidimensional bidding strategy turns out to be capable of making rational decisions with sufficient flexibility in the bidding process. The simulation results validate that the proposed P2P energy exchange mechanism is capable of increasing profits from microgrids and the use of renewable energy sources. Paudel and colleagues [49] propose a game theory model for the P2P energy exchange. There are two separate competencies in the proposed model during the negotiation process: (1) price competition between sellers and (2) seller selection competition among buyers. Furthermore, the authors use a Stackelberg M-leader and N-follower game approach to model buyers' and sellers' interaction. Two iterative algorithms are proposed for implementing the games so that there is a state of equilibrium in each of the games. The results show that P2P energy trading provides significant financial and technical benefits to the community and is emerging as an alternative to high-cost energy storage systems.

2.3.5. Optimization and algorithms

The use of optimization is a fundamental tool to maximize profits or minimize losses. In P2P energy trading, the optimization mechanisms have focused mainly on maximizing the economic benefits of users. It has also been used to achieve the balance between energy supply and demand in microgrids. Another use has been the minimization of energy losses of the prosumers.

Zhou and colleagues [52] propose a new framework for the exchange and coordination of P2P energy on Energy Internet, aiming to achieve flexible and efficient distributed energy management and control. The energy interchange and coordination problem are formulated as an optimization problem whose objective is to minimize users' economic costs. They also propose a distributed algorithm in combination with the alternate direction multiplier method. Based on a real-world dataset of renewable energy and real-time electricity prices, the analytical and numerical results show the effectiveness of the framework and the proposed algorithm in terms of rapid convergence over an interval of time and a considerable economic saving in a long-run. Energy management at smart grids and smart homes will play an essential role in the future energy system. Steinheimer et al. [35] propose an approach for a model to design and generate value-added services to manage smart grids and smart homes. The model offers users the ability to develop services to manage devices and distributed energy resources, as well as to optimize energy consumption through intelligent energy management and automated service generation and optimization. This new approach is based on home networking and algorithms for automated optimization of energy consumption in individual homes or entire areas, without third parties' assistance. Home networking is based on P2P principles for automated communication and optimization, as well as building a social network, such as an energy community. Other researches have focused on evaluating the impact of P2P energy trade between smart homes on a microgrid. Mainly, Alam and colleagues [56] have addressed the problem of optimizing energy costs in smart homes that are connected to share energy. Furthermore, the P2P energy trade in the microgrid results in an unfair distribution of costs among the participating households. To solve this problem, the authors used the Pareto optimality rule. It is shown that cost savings do not always increase linearly with an increase in renewable energy and storage penetration rate.

In another work, Long and colleagues [54] developed a P2P index to assess the viability of the P2P energy trade, where a balance of local electricity supply and demand is desired. The users were classified by their patterns of electric energy consumption and create representative demand profiles. Subsequently, the authors performed a linear programming optimization to find the optimal capacity of different distributed energy resources to maximize local supply and demand balance. Nguyen and colleagues [55] propose an optimization model to maximize the economic benefits for distributed rooftop PV generation with battery storage in a P2P power exchange environment. The objective of their proposed model is to investigate the feasibility of such a renewable source by participating in the P2P energy trade by examining the economic benefits. As a result, it is identified that home energy savings are sensitive to many factors, including the scale of PV systems, PV penetration, P2P business margins, the presence of battery storage, and energy exchange time.

2.3.6. Algorithms

Algorithms have been widely used in P2P trading energy. Blockchain technology uses algorithms to optimize processes. For example, in simulation, it is widespread to use some labels to accelerate the models' convergence. In particular, the algorithms are in constant development to optimize each of the processes that are part of the P2P model.

Liu et al. [57] propose a P2P model with a price-based demand response for solar energy prosumers' microgrids. They formulate a dynamic internal pricing model for the operation in the energy distribution area, which is defined based on the shared photovoltaic (PV) energy supply and demand relationship. Furthermore, considering the flexibility of prosumers' energy consumption, an equivalent cost model is designed in terms of economic cost and user disposition. The algorithm and the implementation method to solve the model are designed in a distributed iterative way. As a result, through a practical case study, the method's effectiveness is verified in terms of saving costs for PV energy prosumers and improving PV energy exchange [57]. Zhang and colleagues [50] devised an effective bidding strategy in the P2P energy trade. In particular, the authors propose a bidding strategy using a two-stage algorithm. In this mechanism, a balance is achieved between fair competition in the market, economic benefits in the participants, and self-sufficiency in the microgrid. Additionally, to help residents make better decisions about their bidding process, this process also offers a trading price predictor and risk analysis tool. Khorasany and colleagues [53] propose an adaptive segmentation method as a market-clearing mechanism for the P2P energy exchange scheme with a large number of market players. In the proposed method, market players participate in the market by announcing their offers. The proposed method is based on developing an adaptive algorithm to divide large numbers of market players into multiple segments to improve the scalability of P2P commerce by reducing data exchange and communication overhead. The proposed approach can be used in conjunction with any distributed method for market-clearing. The authors use two different structures, the community market, and the decentralized bilateral trade market, to demonstrate the proposed method's effectiveness.

The studies where the main focus is optimization and algorithms are closely related to blockchain. Wang et al. [36] proposed a P2P model that is based on an energy crowdsourcing system. In the operation of the systems, the authors used an algorithm that has two phases. The first phase focuses on programming power generation, and the second phase focuses on power distribution in real-time. The designed P2P model uses blockchain technology for its operation. Thakur and Breslin [41] have developed a distributed coalition formation algorithm to be used in a blockchain-based P2P model. The proposed solution applies to microgrids and is more scalable than centralized coalition formation algorithms.

3. Discussion

3.1. Challenges of P2P energy trading

First, trading platforms are a fundamental piece for the implementation of the P2P model in the real-world. The use of blockchain technology has made trading platforms more secure and efficient, but challenges remain [28,30,36]. One of the challenges is to achieve the successful implementation of large-scale commercial platforms, such as cities, states, or countries, since it would allow evaluating the performance of the platforms closest to the real world [59]. At the same time, it is essential to maintain or increase the security levels required by users in a large-scale implementation [28,42,60]. In addition to security, the blockchain system needs to improve data transmission speed to be verified in real-time [60]. Although the algorithms used in blockchain have improved their security and speed in recent years, blockchain still has a high energy consumption, so it is necessary to increase the energy efficiency [28,61]. Blockchain may require new and expensive infrastructure to be embedded in P2P as software or custom information and communication technologies (ICT) [62]. Additionally, the use of smart meters will be necessary, which have reached large parts of the population but do not have the required computational capacity to support blockchain [28]. Blockchain technology depends on the coding of new algorithms to produce improvements. One of the biggest challenges is a solution that combines all the desired characteristics without significant compensation. Research associated with new algorithms to achieve higher speed and security on blockchain platforms is essential [63]. Other types of algorithms that can be improved are data validation and verification since they have a high cost of hardware and energy [64,65]. Data storage is another area of research that can be significantly improved. When carrying out large-scale implementations, it is essential to optimize data storage, which will be in constant expansion after each transaction.

Second, game theory and simulation play an essential role in understanding and modeling participants' behavior in the P2P energy trading model. Game theory studies have focused mainly on users, where different pricing strategies have been applied to determine user behavior [42,66]. Moreover, auction and bidding approaches have been proposed, where prosumers and consumers' behavior has been modeled and simulated. Motivational psychology and game theory models have been used together to model users' behavior in the P2P model more accurately [67–69]. However, the approaches were used are an ideal situation where the participants are rational and always seek to maximize their benefits, which is not always accurate in the real-world because modeling human behavior is a challenge in all areas of knowledge. Achieving modeling more complex user behaviors that are not rational is one of the challenges for the future. In the literature review, two studies that mix motivational psychology with game theory were identified [43,44]. Motivational psychology is a behavioral science branch that studies the psychological process that regulates a human-based behavior based on its perspective, belief, and opinion towards an action [67–69]. Motivation is closely related to behavior; hence, modeling different user motivations allows adding new variables to the P2P energy exchange model. It is essential to continue using motivational psychology to model more complex user behaviors based on motivations. However, few studies mix motivational psychology with game theory, making it a promising topic for future research [43,44].

Finally, facing commercial P2P energy is regulatory restrictions [28,42]. Currently, in most countries, there are no laws or policies that legally allow P2P energy trading. For this reason, it is essential to validate the P2P model in theory and practice so that government authorities and policymakers can know the benefits and impacts of the model in detail to make the necessary regulatory changes.

3.2. Opportunities for P2P energy trading

Future research directions should take into consideration the interests and benefits of users. One possible direction is to explore cooperative games to demonstrate that users can benefit from cooperation, including allowing users to change coalitions and networks to increase personal and collective benefits. Simultaneously, it is critical to demonstrate that P2P energy trading is also beneficial for energy distribution companies and that companies can participate in energy exchange if necessary. Including the conversation, the distribution company can help the actors in the energy system and regulatory entities understand the importance of energy trade between peers. In this way, the P2P model of energy exchange can be approved as part of the energy system. It is also essential that future research on the integration of game theory and blockchain technology to continue to address the current knowledge gaps in the design of efficient commercial mechanisms and the reduction of computational complexity to provide users with a better service. Within the network, there may be a loss of information related to the demand and prices in real-time. To deal with incomplete information, further research is needed to handle scenarios to deal with incomplete information adequately. A possible approach to this problem is a Bayesian game where some players' information is incomplete, and the solution is the Nash Bayesian equilibrium. The incorporation of constraints and new variables could also be considered in future studies. Adding voltage and thermal restrictions and the use of batteries for storage, or the use of electric vehicles, will determine users' behavior in other more complex contexts. Simultaneously, the use of multiple providers of P2P energy trading platforms in the network should be considered, and their impact on user behavior.

Maximization of the benefits of the users and the grid's energy balance are two critical factors to improve the performance of the P2P energy trading model. However, it is crucial to include historical actors such as generation, transmission, and distribution to solve optimization problems. The inclusion of these actors will allow a better transition from the current energy exchange model to the P2P model. Additionally, the development of new algorithms is essential to improve P2P trading energy platforms' speed and security. Algorithms play a fundamental role in improving the performance of blockchain technology. Therefore, it is an area where substantial improvements can be made in future work.

Historical actors of the energy market are generally included in the optimization of energy systems. However, in P2P models, generation, transmission, and distribution are usually not included since most studies consider microgrids as a system where the main actors are prosumers and consumers. In this way, much of the research has focused on maximizing user benefits and maintaining microgrids' energy balance. Future studies would benefit from the inclusion of the use of transmission lines, for example, for the implementation of a P2P model between microgrids. In this model, energy transmission companies play a fundamental role in making energy transactions possible between microgrids.

P2P energy trading is still a challenge for practical implementation worldwide, especially in the United States, where there are fewer academic studies compared to Europe. However, there is currently the potential to make a practical transition from the traditional energy markets to P2P markets where prosumers and consumers are the leading players. It is essential to consider the historical actors of the energy market, such as generation, transmission, and distribution, to avoid possible conflicts since these actors are crucial for a transition to a P2P market. Current regulations do not promote the exchange of energy between peers, so the successful inclusion of historical actors in the model could allow a change in regulations where all actors would benefit. Another area of the current challenges is maintaining high levels of reliability and security in P2P platforms, where it can also be scaled to a large number of users. The present studies have been applied or simulated on a small or medium scale, so it is necessary to understand users and platforms' behavior as the number of participants increases, for example, to a whole city rather than a cluster of dozen neighborhoods.

In summary, P2P trading energy is an area that still needs much work to be successfully implemented in the real-world. One of the opportunities for future research is to analyze the benefits of historical participants in the energy market. Additionally, another area for future research is the combination of P2P markets with existing markets, where consumers can move from one market to another to maximize benefits. Another area for future research is to carry out studies and simulations of scenarios at medium and largescale since most of the studies have been applied to microgrids. Furthermore, there is a lack of sufficient applied researches done in the United States and other developed countries, so there is an opportunity to expand the P2P literature in this area. Finally, one of the critical factors to study is human behavior, which is certainly not easy to model, but having more knowledge about the behavior and preferences of prosumers and consumers is essential to implement the P2P model successfully.

4. Conclusion

Energy distribution systems have changed with the increase of distributed energy resources in the last several decades. The way energy is produced and consumed has changed dramatically. There has been a proliferation of energy prosumers, which have assumed a relevant role in energy generation, providing a more decentralized and open grid. Several researchers have focused on driving the transition to a P2P market to bring prosumers into the power system. P2P energy trading is an essential model to improve the energy system flexibility for a low carbon energy transition. Moreover, P2P allows the proliferation of the use of renewable energies at the residential level.

The overall contribution of this paper was to provide a holistic perspective of challenges and opportunities for implementing the P2P model. Through the review of the literature, themes were categorized into the following topic areas: (1) trading platform, (2) blockchain, (3) game theory, (4) simulation, (5) optimization, and (6) algorithms. The findings from this review can be used to assist researchers, policymakers, and industry advocates in establishing new energy policies and processes related to distributed energy programs. Three additional subcontributions are detailed below:

- In previous P2P review papers, the literature focus has been limited to an isolated topic, such as blockchain technology [28] or the community-based market [20]. This study, on the other hand, offers a holistic study including six critical and interdisciplinary topic areas (e.g., trading platform, blockchain, game theory, simulation, optimization, and algorithms). This holistic overview allows researchers with different backgrounds, technical and socio-economic alike, to collaborate and/or offer insights into joint or overlapping research areas of interest which cross the gamut of technical feasibility, market desirability, and business viability.
- In previous P2P review papers, the literature focus has been limited to specific locations throughout the world [23], or by ignoring the location context altogether. In contrast, this study provides an overview of P2P from a global perspective, providing a contextual emphasis applicable to many countries throughout the world. For example, Fig. 1 provides a summary of worldwide countries which have net-metering regulations (where P2P would potentially thrive the best). Also, Table 1 provides details of P2P projects throughout the world.
- This review study offers a smorgasbord of future research opportunities that can promote convergence research. As presented in sections 2.4 and 2.5, there is a focus on interdisciplinary project opportunities. As an example, game theory allows researchers from diverse disciplinary backgrounds to collaborate (e.g., economics and purchasing decisions, psychology and rational versus irrational behavior, and industrial engineering and system modeling, to name a few). Also, future research recommendations are offered for greater inclusion of energy market stakeholders (e.g., users, consumers, utility operators, grid owners, and regulators). Finally, future research recommendations were offered to highlight the need to conduct project scope to various levels (e.g., individual, commercial, and microgrids).

CRediT authorship contribution statement

Esteban A. Soto: Data curation, Formal analysis, Investigation, Methodology, Writing - original draft. **Lisa B. Bosman:** Conceptualization, Project administration, Supervision, Writing - review & editing. **Ebisa Wollega:** Writing - review & editing. **Walter D. Leon-Salas:** Writing - review & editing.

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.

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