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Peer-to-peer and community-based markets: A comprehensive review

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ABSTRACT

The advent of more proactive consumers, the so-called “prosumers”, with production and storage capabilities, is empowering the consumers and bringing new opportunities and challenges to the operation of power systems in a market environment. Recently, a novel proposal for the design and operation of electricity markets has emerged: these so-called peer-to-peer (P2P) electricity markets conceptually allow the prosumers to directly share their electrical energy and investment. Such P2P markets rely on a consumer-centric and bottom-up perspective by giving the opportunity to consumers to freely choose the way they buy their electric energy. A community can also be formed by prosumers who want to collaborate, or in terms of operational energy management. This paper contributes with an overview of these new P2P markets that starts with the motivation, challenges, market designs moving to the potential future developments in this field, providing recommendations while considering a test-case.

1. Introduction

The continuous integration of Distributed Energy Resources (DERs) [1], e.g., from rooftop solar panels, storage and control devices, along with the advance in Information and Communication Technology (ICT) devices [2] are inducing a transformation of a share of electricity consumers into prosumers. Prosumers undertake a proactive behaviour by managing their consumption, production and energy storage [3,4], while traditional consumers assume a passive behaviour when it comes to their energy consumption.[1] Besides technology-based advances, the collaborative economy principle is influencing how prosumers perceive electric energy [4], from their increasingly engagement with energy community initiatives [5], to their desire of more flexibility on choosing who they are going to exchange energy [6].

Lately, the emergence of this principle is changing the way society trades goods and services [7]. One can see it as a variety of players, with equal access to a common resource and goal of sharing it through a wealth of cooperating infrastructures, which is opposite to the traditional economic principle represented by players with individual goals, and with the resulting equilibrium occurring when all individual goals are satisfied.[2] For instance, there are prominent examples of this paradigm change in our daily lives, with various degrees of collaboration,[3] such as BlaBlaCar,[4] Taskrabbit[5] and Turo.[6]

Although power systems are evolving to a more decentralized management, electricity markets still perform resource allocation and pricing based on the conventional hierarchical and top-down approach [11] of power system management, which makes prosumers behave as passive receivers. Reorganizing electricity markets within decentralized management and collaborative principle will instead allow for a bottom-up approach that would empower prosumers [12]. This may then dynamically influence the market through implementation of prosumers' preferences [13], for instance renewable type, CO_2 emissions and localized energy. Consequently, this alternative market organization is generically named as *consumer-centric electricity markets*, while nearly 20 years ago this visionary concept was mainly seen as a point of academic discussion to weight advantages and drawbacks of

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[1] Prosumer covers a wider-spectrum of consumers with different assets and behaviors, and therefore this term is adopted in the rest of the paper.

[2] For a deeper understanding about collaborative economy and its different classes with their own characteristics please refer to [8–10].

[3] An interested reader may consult an online repository of collaborative platforms at http://meshing.it/.

[4] Carpooling and share the cost of the journey – https://www.blablacar.com/.

[5] Collaboration with housekeeping task – https://www.taskrabbit.com/.

[6] Collaboration with renting cars – https://turo.com/.

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centralized vs. decentralized market structures [14,15].

This consumer-centric market view relies on Peer-to-Peer (P2P) and community-based structures [16,17]. P2P[7] defines a decentralized structure where all peers cooperate with what they have available for commons-based producing, trading or distributing a good or service. P2P and community-based concepts have strongly been applied under a collaborative economy principle[8] as the structure that facilitates the exchange of commons amongst all agents (or peers) [26,27], and they are rather distinct from the centralized structures seen in some traditional economic sectors. In fact, the first reference proposing P2P concept for power systems can be traced back to 2007 [28], as well as there are practical examples using P2P to share energy in local areas, like the iconic case of the Brooklyn microgrid project [29]. However, most countries still prohibit direct energy exchanges between prosumers, though first attempts can be seen in [30,31] to adapt regulation. These initial steps encourage this novel vision of electricity markets as a possible future.

The goal of this paper is to provide a comprehensive understanding of relevant consumer-centric electricity markets.[9] A test-case is included with data to encourage reproducibility and benchmarking in future research on P2P markets. Recent studies [17,32,33] focused more on the market prospects and technological aspects related to integrating prosumers. In contrast, this review enables academic and industrial communities to better understand all aspects related to this transition, to explain how and why they are emerging, and to be capable of proposing new market structures and business models. Although the importance of prosumers is not undermined, this review looks at P2P markets from a wider perspective that includes all involved agents in the power system. Indeed, a peer is defined as anyone owning or operating an asset or group of assets (e.g., production, consumption, storage). More generally, all potential active agents in the market can be seen as peers. As is the case today, some of the agents in the wholesale market do not own and operate assets, instead they trade on behalf of others or possibly are involved in arbitrage and virtual bidding.

The paper is organized as follows, while explaining the review methodology followed by the authors in Appendix A. The premises that support P2P markets, as well as research projects and companies, are discussed in Section 2. An analysis of the different P2P market structures, including a description of suitable optimization techniques for negotiation and market clearing, are described in Section 3. Section 4 identifies the opportunities and challenges that can arise when adopting P2P markets. A benchmark test case illustrating the application of P2P markets is presented in Section 5, which will be available for others to use and test future work in this field. Finally, Section 6 gathers a set of conclusions, as well as recommendations for future work.

2. Premises leading towards peer-to-peer markets

This section explains the premises in terms of economic (bilateral contracts) and technology (microgrids) that enable the emergence of P2P markets in the energy sector. Then, the current Research & Development (R&D) projects and start-up companies in this field are addressed.

2.1. Bilateral contracts and microgrids

Bilateral contracts were introduced with the aim of increasing competition in electricity markets [34,35]. A bilateral contract is an agreement between two parties (buyer and seller) to exchange electric energy, generation capacity rights or related products for a specified period of time, as well as at an agreed price. Under the concept of decentralized systems, Gui et al. [36] analysed the impact of bilateral agreements on community microgrids. This study states that in a microgrid context, the service provider and the consumers will have a strong relationship that can affect incentives and governance models. Wu and Varaiya [14,15] proposed in the nineties a coordinated multi-bilateral trading model as a credible alternative to the pool structure used in the wholesale electricity markets. This model was originally proposed for large players that operate in the market and not for small-scale DERs, but it establishes the premises for a P2P market. Indeed, in its simplest form, a P2P market implies multi-bilateral agreements between agents.

Microgrids are generally accepted as a low voltage distribution grid comprising DERs that can be operated in islanding and grid connected mode [37]. Thus, Distributed System Operators (DSOs) ought to rethink their grid management practice to address this technology transition by adopting novel concepts as addressed in[10] [38,39]. In this context, microgrids are relevant in assisting DSOs [40]. The deployment of microgrids brings infrastructures and technologies in the domains of monitoring, communication and control that are important enablers for P2P markets. The works in [41,42,29] have substantially explored the technological promises brought by microgrids to propose P2P market solutions.

2.2. Research projects and companies with a relation to P2P markets

In recent years, a number of R&D projects have been carried out with twofold purposes, as discussed in [43]: (i) working on the market design and business models for P2P markets; (ii) implementing local control and ICT platforms for prosumers and microgrids. Table 1 summarizes the R&D projects involved in P2P markets.

In the load control and ICT level, EMPOWER[11] developed a real-time platform [44] based on cloud technology to execute the metering and trading within a local community. The P2P-SmartTest project[12] is exploring distributed control with advanced ICT to enable local markets on a distribution grid. The project points out that, in terms of control, the main challenges in distribution grids are the low inertia, uncertainty and stability issues.

In terms of market design proposals, the Enerchain project[13] intends to develop a P2P trading platform to complement, or replace, the wholesale electricity market.[14] On the other hand, NRGcoin[15] aims to develop a virtual currency [45] based on blockchain and smart contracts for small prosumers trading in P2P markets. The Energy Collective project[16] investigates P2P market designs for local energy communities. An educational APP[17] has been developed to educate a broader audience about P2P markets and their promises.

At the same time, start-ups have emerged from R&D projects [46,47] to address P2P energy trading by focusing on the following business areas: (i) P2P exchange of energy surplus, where prosumers can exchange the energy surplus with their neighbours, for example through the companies – LO3 Energy,[18] SonnenCommunity,[19] Hive Power,[20] OneUp,[21] Power Ledger[22]; (ii) Energy provision/matching,

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[7] First application was in computer science to distribute data, and interested readers may consult [18–25].

[8] Examples as Turo and Taskrabbit use P2P structures.

[9] For simplicity, P2P markets to generically refer as consumer-centric electricity markets.

[10] For example, engaging in active distribution network management.

[11] http://empowerh2020.eu/.

[12] http://www.p2psmartest-h2020.eu/.

[13] https://enerchain.ponton.de.

[14] https://enerchain.ponton.de/index.php/21-enerchain-p2p-trading-project.

[15] http://nrgcoin.org/.

[16] http://the-energy-collective-project.com/.

[17] https://p2psystems.shinyapps.io/ShinyApp_Project/.

[18] http://lo3energy.com/transactive-grid/.

[19] https://microsite.sonnenbatterie.de/en/sonnenCommunity.

[20] https://www.hivepower.tech/.

[21] https://www.oneup.company/.

[22] https://tge.powerledger.io/media/Power-Ledger-Whitepaper-v3.pdf.

Table 1
Overview of the R&D projects.

Project name	Country/Region	Starting year	Focus level	Outcomes	Classification
P2P-SmartTest	Europe (Finland, United Kingdom, Spain, Belgium)	2015 (ongoing)	Distribution grid level	Advanced control and ICT for P2P energy market	Local control and ICT; Market design
EMPOWER	Europe (Norway; Switzerland, Spain, Malta, Germany)	2015 (ongoing)	Distribution grid level	Architecture and ICT solutions for provider in local market	Local control and ICT
NRGcoin	Europe (Belgium, Spain)	2013 (finish)	Consumer/prosumer	P2P wholesale trading platform	Market design
Enerchain	Europe	2017 (ongoing)	Wholesale market	P2P wholesale trading platform	Market design
Community First! Village	USA	2015 (ongoing)	Consumer/prosumer	Build self-sustained community for homeless	Local control and ICT
PeerEnergy Cloud	Germany	2012 (finish)	Consumer/prosumer	Cloud-based energy trading for excessive production	Local control and ICT
Smart Watts	Germany	2011 (finish)	Consumer/prosumer	ICT to control consumption in a secure manner	Local control and ICT
NOBEL	Europe (Germany, Spain, Greece, Sweden, Spain)	2012 (finish)	Consumer/prosumer	ICT for energy brokerage system with consumers	Local control and ICT
Energy Collective	Denmark	2016 (ongoing)	Consumer/prosumer	Deployment of local P2P markets in Denmark	Market design
P2P3M	Europe (United kingdom), Asia (South Korea)	2016 (ongoing)	Consumer/prosumer	Prototype P2P energy trading/sharing platform	Market design

where prosumers can directly choose local renewable generation, for example through the companies - Vandebron,[23] Electron,[24] Piclo,[25] Dajie,[26] Powerpeers.[27]

3. Designs for peer-to-peer markets

Following [28,48] and the relevant literature, this section lists and discusses the P2P structures that have been proposed so far for P2P markets: (i) full P2P market; (ii) community-based market; and (iii) hybrid P2P market. The degree of decentralization and topology is what distinguishes them from each other and it can range from full P2P to hierarchical P2P structure.

3.1. Full P2P market

This market design is based on peers directly negotiating with each other, in order to sell and buy electric energy, as shown in Fig. 1.

Hence, two peers can agree on a transaction for a certain amount of energy and a price without centralized supervision. Sorin et al. [49] proposed a full P2P market design between producers and consumers, which relies on a multi-bilateral economic dispatch. The P2P structure includes product differentiation where consumers can express their preferences, such as local or green energy. Morstyn et al. [50] implemented a P2P energy trading for real-time and forward markets of prosumers. Each agent's preferences that capture upstream-downstream energy balance and forward market uncertainty are included in the proposed framework.

In connection with the iconic Brooklyn experiment, a microgrid energy market is developed and published in [29]. This framework enables a local microgrid market without central entity for small agents to trade energy locally. Alvaro-Hermana et al. [51] implemented P2P energy trading between electric vehicles. The objective of the proposed approach is to increase bilateral trade between EVs, instead of them charging from the pool market. The recent research shows that this market design is gaining momentum in the industrial and academic fields. A general mathematical formulation of a full P2P market design is presented below, whereas more details can be found in [49], which in its simplest form reads as

$$\min_{D} \quad \sum_{n \in \Omega} C_n\left(\sum_{m \in \omega_n} P_{nm}\right) \tag{1a}$$

$$\text{s. t.} \quad \underline{P_n} \leq \sum_{m \in \omega_n} P_{nm} \leq \overline{P_n} \quad \forall\, n \in \Omega \tag{1b}$$

$$P_{nm} + P_{mn} = 0 \quad \forall\, (n, m) \in (\Omega, \omega_n) \tag{1c}$$

$$P_{nm} \geq 0 \quad \forall\, (n, m) \in (\Omega_p, \omega_n) \tag{1d}$$

$$P_{nm} \leq 0 \quad \forall\, (n, m) \in (\Omega_c, \omega_n) \tag{1e}$$

where $D = (P_{nm} \in \mathbb{R})_{n \in \Omega, m \in \omega_n}$, with P_{nm} corresponds to the trade between agents n and m, for which a positive value means sale/production (1d) and a negative value is equal to a purchase/consumption (1e). Ω, Ω_p and Ω_c as sets for all peers, producers and consumers, respectively (hence, Ω_p, $\Omega_c \in \Omega$, $\Omega_p \cap \Omega_c = \emptyset$). Fig. 2 shows a simple example to illustrate the P2P trading between 4 peers, in which peers 1 and 2 are producers, peers 3 and 4 are consumers. However, the above formulation can be readily generalized so that all peers are seen as prosumers, i.e., being able to both consumer and produce electric energy.

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[23] https://vandebron.nl.

[24] http://www.electron.org.uk/.

[25] https://www.openutility.com/piclo/.

[26] https://www.dajie.eu/.

[27] https://www.powerpeers.nl/.

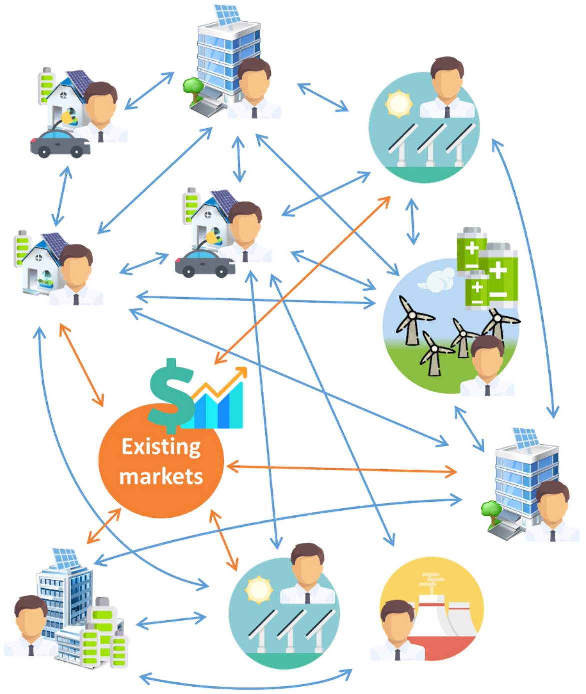

Fig. 1. Full P2P market design.

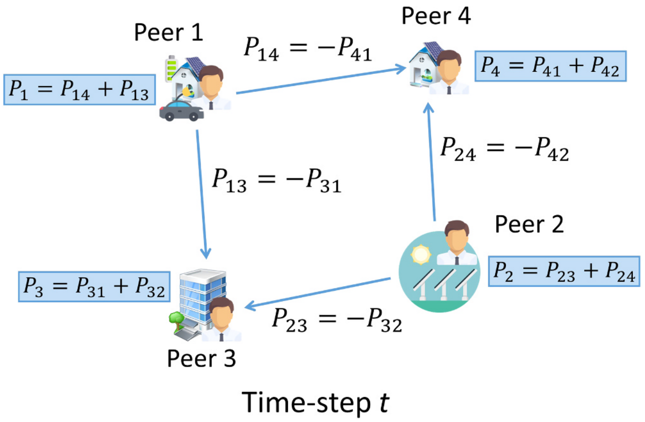

Fig. 2. Illustrative example of a full P2P market design.

The set ω_n contains the trading partners[28] of a certain peer n. The bilateral trades P_{nm} have reciprocity property, as defined by (1c), and for example, the power trades P_{23} and P_{32} have to be equal but with opposite signs. The associated dual variable λ_{nm} represent the price for each bilateral trade. In principle, the outcome of the negotiation process can yield different prices for each and every trade. The function C_n mostly corresponds to the production cost (or willingness to pay). A quadratic function [52] is commonly used to represent production/consumption costs, using three positive parameters a_n, b_n and c_n.

The optimization problem (1a)–(1e) invites the use of decentralized or distributed optimization techniques [53,54] in order to respect the basic nature of a P2P structure. Decomposition techniques such as Lagrangian relaxation, Alternating Direction Method of Multipliers (ADMM) and consensus + innovation are promising candidates. These make it possible to explicitly define individual problems for each agent, while guaranteeing their privacy. Each agent only shares the power and price that it is willing to trade, without revealing sensible information.

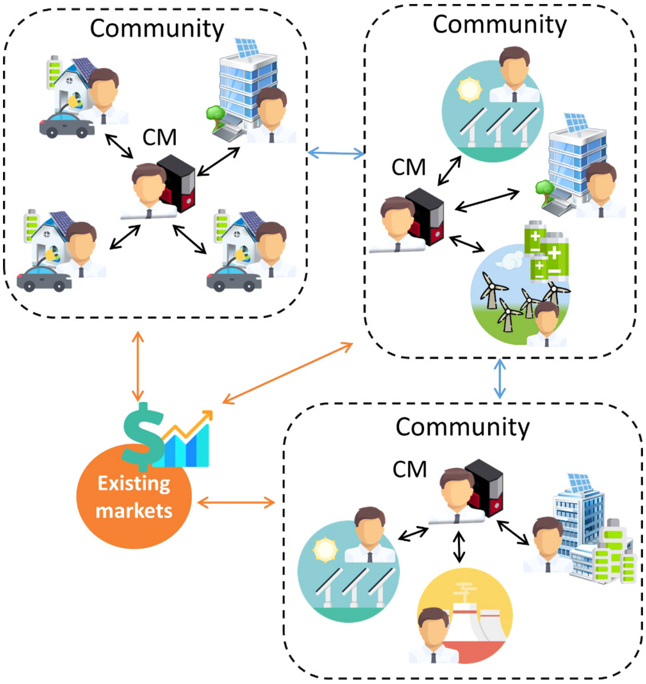

Fig. 3. Community-based market design.

3.2. Community-based market

This design is more structured with a community manager who manages trading activities inside the community, as well as intermediator between the community and the rest of the system, as shown in Fig. 3.

This market design can readily be applied to microgrids [55,56] or to a group of neighbouring prosumers [57,58] that are natural constructs due to their location (i.e. being geographically close). More generally a community is to be based on members that share common interests and goals: for instance, a group of members that are willing to share green energy, though they are not at the same location. Moret and Pinson [59] formulated a community-based market with prosumers working in a collaborative manner. On the other hand, a multi-class energy management of a community-based market is designed by Morstyn and McCulloch [60]. The proposal formulated three different classes of energy to translate the prosumers' preferences. Tushar et al. [61] implemented an auction scheme to share energy storage in a community. These are composed of agents with storage devices on the one hand, and on the other hand of agents willing to use those shared energy storage. A general mathematical formulation of a community-market design, following [59], can be written as

$$\min_{D} \sum_{n\in\Omega} C_n\left(p_n, q_n, \alpha_n, \beta_n\right) + G\left(q_{\text{imp}}, q_{\text{exp}}\right) \tag{2a}$$

$$\text{s. t. } p_n + q_n + \alpha_n - \beta_n = 0\,, \quad \forall\, n \in \Omega \tag{2b}$$

$$\sum_{n\in\Omega} q_n = 0 \tag{2c}$$

$$\sum_{n\in\Omega} \alpha_n = q_{\text{imp}} \tag{2d}$$

$$\sum_{n\in\Omega} \beta_n = q_{\text{exp}} \tag{2e}$$

$$\underline{P_n} \le P_n \le \overline{P_n} \quad \forall\, n \in \Omega \tag{2f}$$

where $D = (p_n, q_n, \alpha_n, \beta_n \in \mathbb{R})_{n\in\Omega}$. p_n corresponds to the production or consumption of peer n, depending on whether it is a producer or

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[28] Consumers have as trading partners the producers and prosumers. Conversely, prosumers and producers have consumers as trading partners.

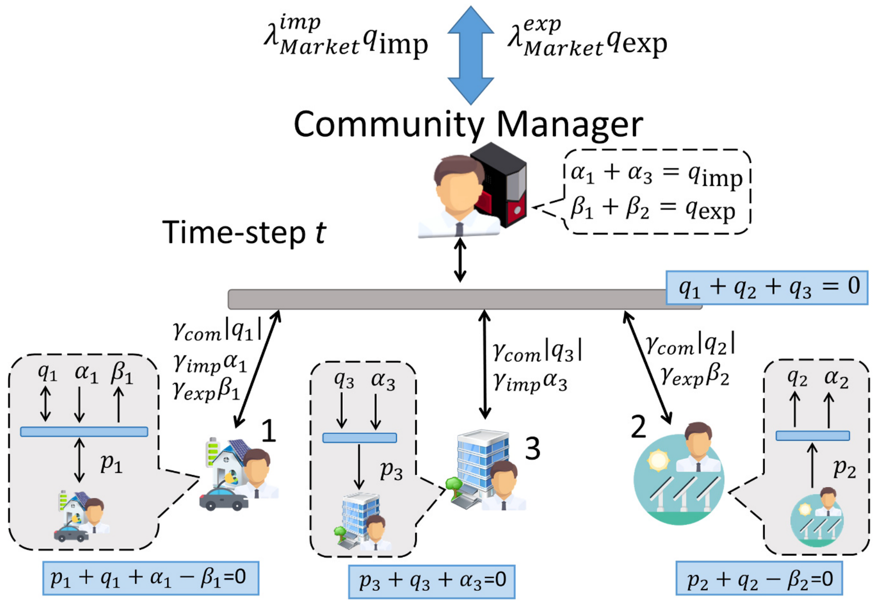

Fig. 4. Illustrative example of a community market structure.

consumer, respectively. Ω is the set corresponding to all peers in the community. Fig. 4 shows a small community as illustrative example.

Each agent trades within the community through q_n without knowing to which member, because it is centrally handled by the community manager through (2c). Each peer can also choose to trade with the outside through α_n and β_n, which are respectively the power import and export. The sum of these trades is centrally handled by the community manager through (2d) and (2e). The objective function (2a) accounts for the cost associated with all decision variables. Starting with a quadratic cost function of p_n, then a transaction cost γ_{com} associated to q_n. For α_n and β_n, one can use weighting coefficients γ_{imp} and γ_{exp} translating the member's preference towards the outside world. The community manager also has a function associated to the energy exchanged with the outside world $G(q_{\text{imp}}, q_{\text{exp}})$. This function can be modeled in different ways, but the most straightforward one readily links to day-ahead wholesale market prices.

As for the previous design, the negotiation process can be solved in a distributed manner [54], for which there is a central node (community manager) to manage the remaining ones (agents). Each agent solves its own problem and only shares the required information with the central node. One can employ ADMM or similar distributed technique to solve the community-based problem in (2a)–(2f).

3.3. Hybrid P2P market

This design is the combination of the two previous designs, ending up with different layers for trading energy, as shown in Fig. 5. This proposal is seen as a "Russian doll" approach, where in each layer communities (or energy collectives) and single peers may interact directly with each other.

In the upper level, one finds individual peers or energy collectives engaging in P2P transactions between themselves, and also interacting with existing markets. In the bottom level, the energy collectives behave like the community-based approach previously introduced, where a community manager oversees the trading inside its community. As shown on the right of the picture, energy collectives can be nested into each other (e.g., buildings and their inhabitants forming an energy collective, being part of another energy collective for the neighborhood). Although, there is no generic mathematical formulation to this hybrid P2P design, one can combine the two previous formulations to write a simplistic version of this design. Two levels are assumed in this formulation: (i) the bottom level only assumes communities using (2a)–(2f); (ii) the upper level assumes a P2P negotiation between individual peers and community managers using (1a)–(1e). The simplest form of this formulation reads as

$$\min_{D} \sum_{n\in\Omega^u} C^u_n\left(\sum_{m\in\omega_n} P_{nm}\right) + \sum_{n\in\Omega^b} C^b_n\left(p_n,\, q_n,\, \alpha_n,\, \beta_n\right) \tag{3a}$$

$$\text{s. t.}\quad \text{upper level - full P2P design:}$$

$$\text{constraints in (1a)} - \text{(1e)} \qquad \forall\, n \in \Omega^u \tag{3b}$$

$$\sum_{m\in\omega_n} P_{nm} = q^n_{\text{exp}} - q^n_{\text{imp}} \qquad \forall\left(n,\, m\right) \in \left(\Omega_{co},\, \omega_n\right) \tag{3c}$$

$$\text{bottom level - community-based design:}$$

$$\text{constraints in (2a)} - \text{(2f)} \qquad \forall\, n \in \Omega^b \tag{3d}$$

where $D = (P_{nm} \in \mathbb{R}_{n\in\Omega^u},\, p_n,\, q_n,\, \alpha_n,\, \beta_n \in \mathbb{R}_{n\in\Omega^b})$. Ω^u and Ω^b are sets for all peers in the upper and bottom level, respectively (hence, $\Omega^u \cap \Omega^b = \Omega$). In the bottom level, the community manager of each community $n \in \Omega^b$ determines the internal energy needs[29] q_n plus the desire energy import (q^n_{exp}) or export (q^n_{imp}). Then, the full P2P market formulation is used in the upper level to calculate the optimal P2P energy trading between the peers $n \in \Omega^u$ (i.e. individual prosumers and community managers). The sum of bilateral trades $\sum_{m\in\omega_n} P_{nm}$ is equal to the amount of q^n_{exp} minus q^n_{imp} defined by the community manager of each community n (3c).

Some authors started to explore this nested approach, such as Long et al. [62] with a hybrid design containing three distinct levels for a distribution grid. The upper level assumes the grid divided into cells trading among themselves. In the second level, trades happen between microgrids under the same cell. At the lower level, a community-market design is applied for each microgrid. In [63], an hybrid approach is proposed for microgrids under the same distribution grid, where the grid constraints are included in the P2P trading between microgrids. This work uses a relaxed formulation of an AC optimal power flow and it removes the price and negotiation mechanism between microgrids.

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[29] This corresponds to the community internal consumption or production.

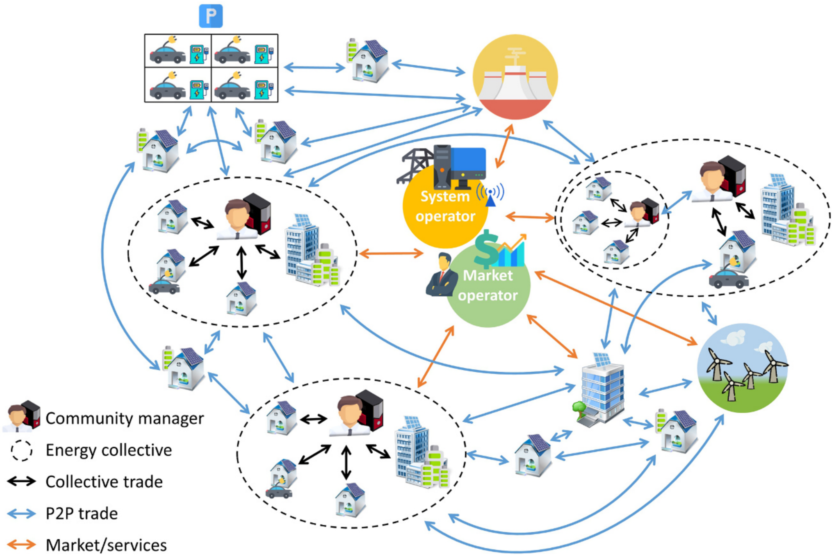

Fig. 5. Hybrid P2P market design.

Table 2
Summary of three P2P market designs (based on [48]).

P2P market structure	Main advantages	Main challenges	Refs.
Full P2P market	1) Total freedom of choice and autonomy, empowering the active consumers; 2) Energy use aligned with each agent's preference (e.g. cost, green, local, etc); 3) Complete "democratization" of energy use	1) Investment and maintenance with ICT infrastructure in case of scalability to all system; 2) Potential slow convergence to obtain a consensus in the final delivery of energy; 3) Predicting system behaviour by grid operators, because of the lack of centralized control; 4) Guarantee of safety and high-quality energy delivery	[29,49,64,50,51]
Community-based market	1) Enhancing the relationship and involvement of community members, because of sharing a common good (i.e. energy); 2) Mobilizing social cooperation and resilience in community members; 3) Potential new services for grid operators provided by the community manager	1) Reaching the preferences of energy use for all community members at all time; 2) For the community manager is aggregating all members' data and managing their expectations; 3) Having a fair and unbias energy sharing among community members	[41,42,55,57,56,58,65,59–61]
Hybrid P2P market	1) ICT infrastructure and computation effort are scalable to all system; 2) Most compatible with the system in the next years, it can be seen as co-existent design of the two previous ones; 3) More predictable to the grid operators	1) Coordinating internal trades in the communities with trades between high-level agents (e.g. community managers, utilities, etc)	[62,63]

3.4. Comparison on P2P market designs

The literature converges so far on three different market designs for P2P markets, even if some references use different terms to describe the same type of market structure. The main advantages, challenges and references of the three P2P market designs are presented in Table 2.

The first design gives the possibility that the energy usage is truly aligned with consumers' preferences. On the other hand, there is a scalability problem concerning the negotiation process, as analysed by the authors in [66]. The negotiation can become a computational burden for scenarios with many participants in this design. If this design is used for the entire power system, the scalability is a real challenge yet to be solved. One way to handle this issue could be through sparse graphs to reduce the number of communications.

On the other hand, the main advantages of the community-based market design are the enhancement of involvement and cooperation of community members. The fact of being a more structured design allows the community manager to provide services to the grid operators as an aggregator. The revenues from these services can be shared (e.g., in a proportional way) by all community members. Even if all members agree to participate in a community, there may be times when a member's expectation is not aligned with the community's general interests.

The final design shares some of the advantages of the two previous designs such as empowering choice of agents, increasing their involvement and cooperation. Besides that, the scalability of all the system is in a way covered by this design, because the ICT and computational effort required are less than required by the full P2P market design. The two previous market designs can co-exist and interact in such a hybrid structure, where the coordination of trades at and between levels is important.

Another important aspect to mention is related the ICT infrastructure that must sustain these market designs. The proposals explored have in common two main pillars, i.e the physical and virtual layers. In most of the cases, the protocols proposed for smart grid applications are used in the physical layer [32], while blockchain technology[30] [67,68] has received attention as potential solution for the virtual layer. This technology is the backbone behind the crypto-

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[30] It is a distributed platform for data management that can register and settle transactions between peers.

Table 3
Summary of potential strengths, weaknesses, opportunities and threats.

Strengths	Weaknesses	Opportunities	Threats
1) Empowerment of consumers, focusing in trust, transparency and openness	1) Sub-optimal energy price of all energy system	1) Democratization of energy	1) Legal and regulatory obstacles, which influence the transition to these markets
2) Consumers have better choice of supply and possibility to produce and sell their own energy	2) Potentially overwhelming transition to this consumer-centric market	2) Increase consumers awareness and cooperation towards environmental energy consumption	2) Energy poverty for some group of consumers
3) Increase resilience and reliability of the system	3) Heaviness of negotiation and clearing mechanisms	3) Create new business models	3) Prosumer engagement and its human dimension
4) Remove potential market power from some players in the wholesale market	4) Life-cycle assessment of hardware infrastructure	4) Boost retailer market, since lacks competition	4) Potential grid congestions
		5) Postpone grid investments from system operators	5) Technology dependency (e.g. blockchain)
			6) Security and privacy with data
			7) Potential failure of these markets if poorly structured

currencies that have appeared in recent years.[31] Some literature argue that blockchain can be the key factor to deploy a P2P market in the energy sector [69–71]. There are enormous advantages such as data management without third-party supervision, but caveats such as scalability and data storage need to be addressed before a real implementation in the energy sector [72]. Although, many consider blockchain the most important asset in a successful deployment of P2P markets, it is worth mentioning that such markets can exist without blockchain.

4. Opportunities and challenges

This section focuses on future prospects with P2P markets, by starting with an analysis of opportunities and remaining challenges. Then, topics worthy of investigation by the research and industrial communities in the coming years are introduced and discussed.

4.1. Discussion on P2P market potential

For a better analysis of potential opportunities and challenges about this topic, an analysis based on Strengths, Weaknesses, Opportunities and Threats (in short SWOT) was elaborated that is shown in Table 3. The main enablers and obstacles supported the analysis concerning P2P market potential that is described in the next sections.

The empowerment of consumers choice and transparency is an obvious strength of P2P markets, because of their flexibility that enables consumers choice on the type and origin of their electricity in a dynamic manner. Thus, consumers create empathy towards those who collaborate, particularly when they receive positive feedback. Brudermann et al. [73] indicated five different classes of collaboration among consumers in P2P markets for an urban area. The system resilience and security can improve, because consumers will be compelled to solve problems and not jeopardize the normal operation of others, especially the ones they know from previous transactions. There are cases like unexpected loss of renewable production or congestion problems in the grid that can be solved in a collaborative manner by all involved peers (i.e. large producers and small prosumers). This may lead to a rethink of the top-down hierarchical structure used for grid operation. Finally, prosumers will be less volatile to the wholesale market price, because they found alternative solutions to their energy supplier by engaging in P2P trading/sharing approaches.

The P2P design allows product differentiation reflecting consumers' preferences in energy trading that leads to different prices for every transaction. However, this aspect can also lead to a sub-optimization of the overall energy price, which represents an obvious weakness in these markets. The fact that all market participants simultaneously negotiate with all others can help prices to converge to similar values. Further investigation is required to determine the magnitude of this sub-optimal price. The overwhelming number of transactions and the heaviness of the negotiation mechanism are other weaknesses as investigated in [66]. The first one is particularly important for a full P2P design, but it can be mitigated in other less ”anarchical” designs, like community-based or hybrid P2P. The life-cycle assessment of certain hardware supporting the negotiation process (e.g. smart devices, batteries, PV panels, etc) can be a weakness in such P2P markets, which future investigation has to pay attention to. The economy of scale in this P2P markets approach can be one way to mitigate this weakness.

This new form of market can create opportunities for all participants in the electric power system. The first opportunity is more democratization of energy by adopting such a market approach. The introduction of such new markets also creates the possibility of having new business models. Currently, the retail market lacks competition in many countries, for which the P2P market can be a solution. Retail companies may have to adapt their business to more P2P transactions. Finally, the grid operators can benefit from such markets by deferring grid investments in new lines and equipment. One of the strengths is the increase in resilience and security, which creates an opportunity to solve grid problems by all market participants rather than reinforcing the grid.

On the other hand, the main threat concerns the legal framework in most countries. However, the authors believe that with time this obstacle will be less and less important and eventually removed. Energy poverty of some consumers or communities with less economic power can arise when P2P markets are implemented. In addition, consumer and prosumer engagement, i.e. their willingness to participate and fully utilize the possibilities offered by such a decentralized, is also a point of concern since interest in electricity matters is commonly low. Different studies [74–77] emphasise how important it is to account for human behaviour in electricity markets. The EU is also committed, with several projects, to bridge the gap between technology-based potential of consumer programmes and actual market behaviour. More precisely, this was the central focus of projects such as BEHAVE,[32] Penny[33] and PEAKapp.[34] P2P market development ought to account for the insights gained through this type of projects, to eventually reduce the potential of this threat. Bounded rationality of electricity consumers and prosumers may also play a role in market design and operation [78]. Finally, academic and industrial partners that work on this topic must be aware

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[31] The most famous type of crypto-currency is bitcoin.

[32] https://ec.europa.eu/energy/intelligent/projects/en/projects/behave.

[33] http://www.penny-project.eu/.

[34] http://www.peakapp.eu/.

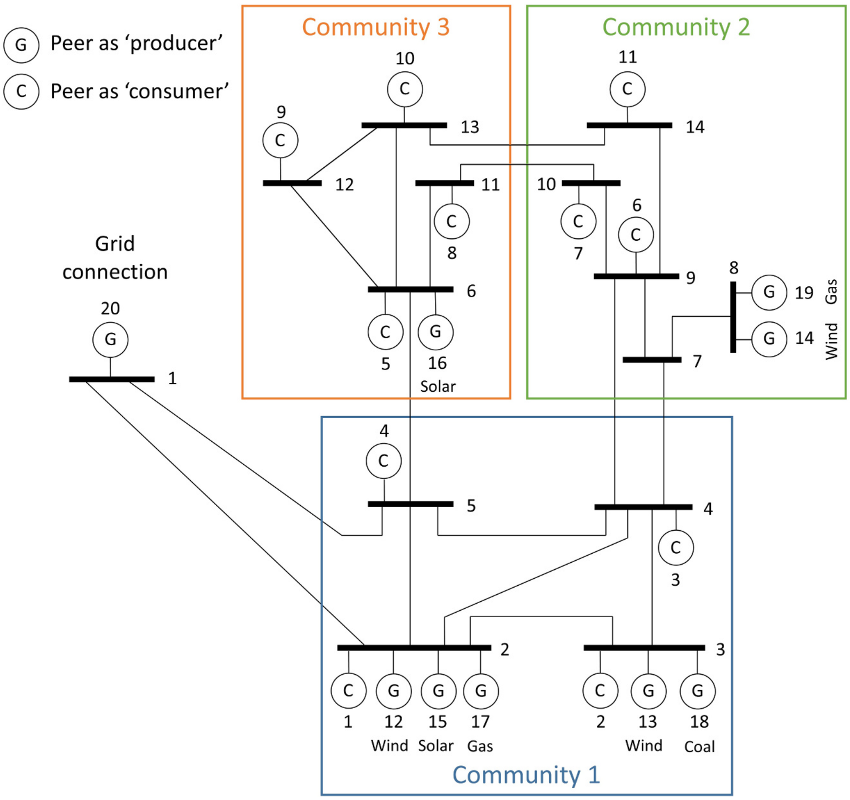

Fig. 6. IEEE 14-bus network system.

Table 4
Results of all P2P market designs.

Market designs	Total SW [M$]	Import cost [M$]	Export revenue [M$]
Full P2P	45.21	0.072	56.66
Community	44.27	2.88	58.95
Hybrid P2P	44.32	2.86	58.71

Table 5
Energy trade for all P2P market designs.

Market designs	Total load [GW h]	Total import [GW h]	Total export [GW h]	Community exchange [GW h]
Full P2P	401.4	2.1	1041.1	54.4
Community	395.1	45.4	1093.4	0
Hybrid P2P	395.7	44.7	1085.5	9.1

that a poor design can cause a potential failure in P2P markets. Poorly designed markets could indeed have an effect on system resilience and power system security that is the opposite of what P2P systems are normally praised for. The exploitation of the positive aspects (strengths) and resolution of the handicaps (weaknesses) would result in successful implementation of P2P markets in its different structures. The next subsections discuss new directions based on this analysis that are worth exploring in the coming years.

4.2. Recommendations on business models and grid operation

So far, the paper has explored the implementation of P2P markets as alternative structures to the existing ones in the electricity market, i.e. wholesale and retail. On top of this layer, the electricity market has different type of business models operated by different actors (e.g. utilities, retailers, etc). The business models can be classified as C2C, B2C and B2B based on how different kind of market actors trade good or services, where C2C, B2C and B2B stands for Consumer-to-Consumer, Business-to-Consumer and Business-to-Business, respectively. For the electricity market, a retailer with a business model that intermediates the energy trading between an electric utility and small consumer is classified as B2C business model. This can be operated in one of the structures defined for the electricity market (e.g. wholesale, retail or P2P). Today, the existing B2C business models heavily rely on the centralized pool-based structure used in the wholesale market, thereby prosumers are unaware, and cannot select directly which utilities real provide their energy. On the other hand, there are companies (e.g. Vandeborn and Piclo), as shown in Section 2, using P2P designs that offer as business the intermediation of the energy trade between small consumers and local renewable producers, whereas it is within a C2C business context. This has a residual effect in the entire electric power system, because of the small scale P2P application and lack of direct connection through B2C models. Therefore, researchers has been challenging decision-makers to see P2P as a new channel for B2C business models that could allow large utilities to directly trade energy with small prosumers. This could be done through direct mechanisms for real-time negotiation and endogenous consideration of preferences, instead of the statistical accounting performed today for the case of guarantees of origin. However, new B2C business models have, in its essence, to follow the consumer-centric premise that characterizes P2P markets. Thus, it would create a sense that everyone is part of (and benefits from) this energy revolution towards a more sustainable electricity sector.

Grid operation under a P2P market is still a concern, mainly to grid operators. There are only few studies assessing the impact of P2P trade on grid operation [79,80]. In fact, grid congestion can be a potential threat if not properly handled, as indicated in Table 3. However, P2P markets also present a new opportunity to rethink the use of common

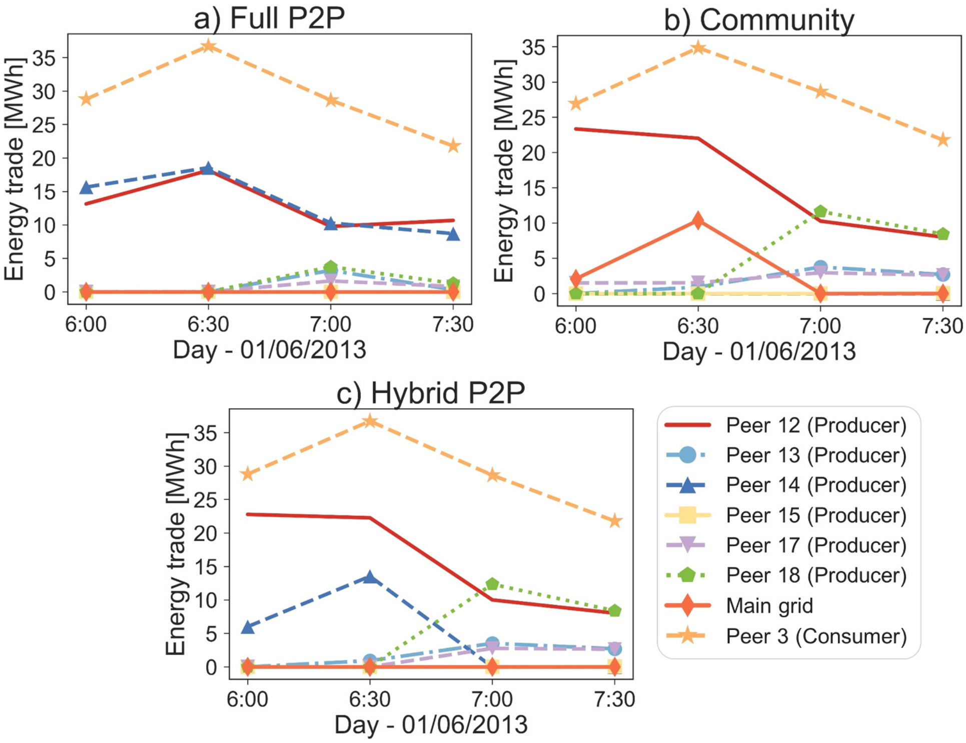

Fig. 7. Trades negotiated by consumer 3 at day 01/06/2013 from time step 6:00 to 7:30: a) full P2P, b) community and c) hybrid P2P.

grid infrastructures and services, because P2P structures may allow the mapping of the energy exchanges. For example, the grid cost may depend on electrical distance associated to each P2P transaction. The recent breakthroughs concerning distributed optimization on grid operation [81] can also inspire other works on the redesign of grid operation under P2P markets. Rethinking grid operations can deploy new business models, where communities or individual agents participate in flexibility services to respect the grid operation. This represents another opportunity to mobilize customers' flexibility and resilience through increased awareness and involvement.

5. Reference test case for P2P markets

In this section, the three P2P market designs described in Section 3 are evaluated on the IEEE 14-bus network system presented in [82]. This test case provides a realistic case to simulate P2P market designs, since there does not exist today a reference test case that would encourage reproducibility and benchmarking. The bus 1 is the upstream connection with the main grid, where the generator assumes an infinite power.[35] Fig. 6 shows the IEEE 14-bus system divided into three communities, containing 19 peers represented by their ID and type.[36]

The test case is simulated over one year with 30 min time-step based on available Australian data. More precisely, the production levels of wind turbines and PV plants, as well as the consumption of households, are taken from [83,84]. These data sets have been normalized and then scaled to the capacity of the wind turbines, PV plants and loads. A quadratic cost function is used to characterize the cost function of all resources, however the PV and the wind turbines are modeled as must-take producers ($\underline{P}_n = \overline{P}_n$ and $a_n = b_n = 0$). The linear cost b_n of peer 20 in bus 1 is equal to the market price from July 2012 to June 2013 provided by the Australian Energy Market Operator. This test case assumes a tariff of 10 \$/MWh for using the main grid. Thus, the importation price from the producer in bus 1 is equal to the market price plus the grid tariff. On the other hand, the export price is equal to the market price minus the grid tariff. Readers interested in using the data presented in the test case for further research are directed to [85].

The three market designs presented in Section 3 are simulated using the mathematical formulation (1a)–(1e), (2a)–(2f) and (3a)–(3d). The three communities defined in the test case are only used for the community and hybrid P2P designs. In the former, each community only trades with the main grid. In the latter, the three communities trade with each other and the main grid. Besides the quadratic cost function, the cost of $\gamma_{com} = 0.001\$/\text{MW h}$ is applied to all P_{nm} in the full P2P design, as a transaction cost. For community and hybrid P2P designs, the same transaction cost is assumed for the energy traded (q_n) within each community (2c). Besides that, the hybrid P2P design has transaction costs for the P2P trades between the three communities:

- Community 1–2: 2 \$/MW h.
- Community 1–3: 1 \$/MW h.
- Community 2–3: 1.5 \$/MW h.

Each design is then solved by a centralized optimization approach. Table 4 shows the results of all simulations, namely the social welfare, total import cost and export revenue to the main grid.

The highest social welfare is reached with the full P2P design, while the community design presents the lowest result with a difference around 2%. This is true, since the communities only trade with the main grid, while in the full P2P design it is possible to share the renewable surplus among all peers. In this test case, the exportation to the main grid is less profitable than trading with other peers between the three communities. Therefore, the hybrid P2P design improves the social welfare when compared to the community design. This improvement is affected by the extra transaction costs of 17.4k\$ between communities. When this cost is removed, the social welfare of the hybrid P2P design is similar to the full P2P design. The energy exchange in all P2P market

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[35] For this generator, the lower and upper bound $\underline{P}_n$ and $\overline{P}_n$ are equal to $-\infty$ and $+\infty$, respectively.

[36] The symbols (G) and (C) are used in the figure to represent the peer as a producer and consumer, respectively.

designs is shown in Table 5, namely the total load, import, export and energy trade between communities.

The full P2P design achieved the highest consumption, due to the same reason (sharing renewable surplus) mentioned before in Table 4. This fact influences the low energy import and high energy exchange between communities achieved in this design. On the other hand, the community design presents the highest results for the energy import and export. When both designs are compared, the energy import and export are reduced by 95% and 5%, respectively. The energy exchange between communities in the full P2P design (54.4 GW h) is almost the same as the energy export decrease (52.3 GW h). To illustrate the differences in trade among peers between the three P2P designs, the trade negotiated by peer 3 at day 01/06/2013 from time step 6:00 to 7:30 is shown in Fig. 7. The peer 3 belongs to the community 1 and its total consumption is represented by a yellow line, which also corresponds to the sum of all other lines.

The main difference between the three designs is the energy trade with peer 14 located in community 2 (represented by a blue line). For the full P2P design (Fig. 7 a)), peer 14 is one of the top agents that peer 3 trades with during these time steps, namely at 6:00 and 6:30. In the hybrid P2P design (Fig. 7 c)), the amount of trade with peer 14 is reduced because of the transaction cost of 2 $/MW h for the energy trade between community 1 and 2. To avoid this extra cost, peer 3 trades more energy with the peers of the same community 1 (i.e. peers 12, 13, 15, 17 and 18). Similar behaviour can be seen in the results of the community design (Fig. 7 b)). In conclusion, the best result is obtained by the full P2P design when all peers share the renewable surplus. However, one should not conclude that this is the best design, since the main objective is to have a real test case for assessing different P2P designs. Moreover, the results may change when the network constraints are included in these market designs. Other researchers are free to use this test case in their investigations such as to validate new market designs and business models, or to assess new grid operation strategies.

6. Conclusions and perspectives

The current paradigm has the drivers to conduct the transition towards P2P markets in order to bring prosumers into power system operational practice. This paper contributes to such a discussion through a detailed review of P2P market proposals, as well as pointing at future areas of relevant research. Furthermore, it is concluded that there are conditions to deploy P2P markets in co-existence with existing market structures, as long as potential conflicts with historical actors are prevented since these are key to a smooth and manageable transition towards P2P markets. Future research should promote ways for P2P markets to be coupled with the existing wholesale and retail markets, allowing consumers to switch from one market to the other when it is most convenient.

Moreover, this study shows that P2P market may give a new taste to B2C business models for electricity, most likely with greater regard for consumer preferences and interests. Further contribution should be promoted on how to quantify the benefits and impacts of new forms of B2C models. One should also pay attention to how system operators could be involved in P2P markets, and satisfying them in terms of feasibility, reliability and security of supply. Most importantly, how to maintain high levels of power system reliability through the distributed provision of reserves. For example, probabilistic matching and queueing theory could be pursued as new hypotheses to solve imbalances of different prosumers in a collaborative manner.

From this literature review, one concludes that the hybrid P2P market design is the most suitable in terms of scalability, giving room for all other P2P designs to interact. Besides that, P2P designs invite the use of distributed optimization techniques that respect the privacy of every peer, and future work should aim to improve the negotiation processes. Arguably, scalability when reaching large number of peers is a current challenge. Sparsification of communication and negotiation graphs will be fundamental to reduce exchanges among peers with residual effect on the optimality of resource allocation and pricing outcomes. The research of methods to handle asynchronous communication is also a relevant future work. The last relevant area of future research should target the human dimension modelling of consumers, such as bounded rationality and strategic behaviour, which may drift towards the social science side to find ways to optimally express consumer preferences and appraise the impact of such preferences on market functioning and outcomes.

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Appendix A. Review methodology

This review methodology follows the procedures outlined in [86,87]. The review started by gathering technical reports, scientific papers and books from different fields, since the original goal was to invest in a broad and interdisciplinary review on P2P electricity markets. This included literature on energy, power systems, economics, operational research, computer and social sciences. At this stage, only peer-reviewed journal articles, books and conference proceedings in English were analysed in this review. This search led to a total of 112 publications. The next step was the analysis of each document to evaluate its relevance to the topic. Categories related to the research topic were defined[38] and every publication was associated with at least one category. Three labels classified the literature to quantify their relevance in each category: A for a publication with high quality, B for a publication with some relevance to the category but important to the context of the review, whereas C for limited relevance, which led to exclude them.

After this process, a total of 80 publications remained that were of high relevance, where there are 69 references with label A plus 11 references with label B. Focusing in references with label A, while 15 publications related to P2P markets were published until 2015, nearly a total of 54 publications was published after 2015. This reveals increased interest from the scientific and industrial communities in P2P electricity markets. Many papers discuss the main drivers, barriers and market designs for P2P electricity markets. Yet, there are other research questions not addressed by the literature, such as life-cycle assessment of hardware and economy of scale, and these other aspects were not extensively covered in this paper.

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[37] https://www.flaticon.com/.

[38] For example, the categories ‘premises to P2P markets’, ‘projects and companies’, ‘P2P market designs’, etc.

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