Using peer-to-peer energy trading platforms to incentivise prosumers to form federated power plants[1]

Thomas Morstyn[2]*, Niall Farrell[3], Sarah J. Darby[4] and Malcolm D. McCulloch[2]

Power networks are undergoing a fundamental transition, with traditionally passive consumers becoming 'prosumers' – proactive consumers with distributed energy resources, actively managing their consumption, production and storage of energy. A key question that remains unresolved is, how can we incentivise coordination between vast numbers of distributed energy resources, each with different owners and characteristics? Virtual power plants and peer-to-peer energy trading offer different sources of value to prosumers and the power network and have been proposed as different potential structures for future prosumer electricity markets. In this Perspective, we argue they can be combined to capture the benefits of both. We thus propose the concept of the federated power plant, a virtual power plant formed through peer-to-peer transactions between self-organising prosumers. This addresses social, institutional and economic issues faced by top-down strategies for coordinating virtual power plants, while unlocking additional value for peer-to-peer energy trading.

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[2] Department of Engineering Science, the University of Oxford, Parks Road, Oxford OX1 3PJ, United Kingdom.
[3] Institute for New Economic Thinking at the Oxford Martin School, the University of Oxford, Eagle House, Walton Well Rd, Oxford OX2 6ED, United Kingdom.
[4] Environmental Change Institute, the University of Oxford, South Parks Road, Oxford OX1 3QY, United Kingdom.
* e-mail: thomas.morstyn@eng.ox.ac.uk

Power networks face the Energy Trilemma, the challenge of transitioning to zero carbon emissions generation while continuing to provide universal and secure access to affordable energy [1]. Two technology trends present new opportunities to address this challenge: distributed energy resources (DERs) and consumer level communications and control. DERs include distribution network generation sources, energy storage systems and flexible loads. DERs have seen significantly increasing adoption due to technological developments and increased scales of production [2]. Consumer level communications and control includes the adoption of smart meters and energy management systems [3].

Together, these trends allow traditionally passive consumers to become 'prosumers' – proactive consumers with DERs who actively manage their consumption, generation and storage of energy [4]. While a number of definitions exist [5], prosumers are most broadly defined as including consumers that schedule flexible loads, and those that monitor and share information on their energy usage, since these activities can directly influence power system operation [6].

Even in liberalised electricity markets, a number of barriers inhibit DERs from participating directly in wholesale markets for energy, transmission rights and ancillary services [7]. Individual consumers and small-scale generators have little individual impact at the transmission level, and the complexity of the processing and communications infrastructure needed for participation would involve transaction costs that outweigh potential benefits. Furthermore, market price fluctuations present risks that are difficult to hedge at the individual level. Instead, they have traditionally been serviced in retail markets by large suppliers, where economies of scale allow for transaction costs to be overcome and market price risks to be diversified.

However, prosumers in the retail market are individually metered by a supplier and therefore only benefit from their flexible capacity to the extent they are able to shift their own demand to reduce their energy costs. If prosumers do not benefit from being part of power transmission and distribution networks, those with sufficient generation and storage capacity will have an incentive to go off-grid [8]. This is an inefficient outcome, both for prosumers and the power network. Off-grid prosumers will require capacity to meet their peak anticipated demand – capacity that will be idle much of the time and unavailable to others. If prosumers migrate off-grid, fixed network costs will be shared by fewer remaining consumers, reducing the value for money offered to them by the network [9].

Coordinating local DERs to reduce upstream generation and transmission capacity requirements could provide significant value, by increasing network efficiency, reducing pollution and increasing energy security [10]. The concept of coordinating DERs into virtual power plants (VPPs) has been proposed to achieve this. A VPP is a collection of DERs that are coordinated to have visibility, controllability and impact at the transmission level of the power network [11]. VPPs include demand response aggregators, which focus on flexible loads [12].

A range of strategies have been proposed for coordinating DERs into VPPs. These can be broadly divided into two groups: direct strategies that control individual DERs, and indirect strategies that send signals to influence the consumption/generation decisions of prosumers [13], [14] (time-of-use prices are a simple example). Different strategies have advantages for particular applications. However, key social, institutional and economic issues remain unaddressed [15]. In particular, existing VPP coordination strategies require top-down design and implementation by a single entity, which defines the terms of VPP operation. However, the electricity market participants who are best placed to implement VPPs may not be incentivised to arrange for a socially optimal level of DER participation, since it could conflict with their existing operating models. It is individual prosumers that have the greatest incentives to realise the full potential value of the DERs they own.

Peer-to-peer (P2P) energy trading platforms allow prosumers to trade electrical energy with one another directly. Energy transactions could vary in terms of quantity, time-scale and acceptable variability, and may be network location-specific. P2P energy trading is recognised as another potential structure for prosumer electricity markets [16]. P2P trading platforms have emerged in a range of sectors, allowing small suppliers to compete with traditional providers of goods and services [17].

In this Perspective, we argue that although P2P energy trading and VPPs offer different sources of value to prosumers and the power network, these structures are not necessarily strict alternatives. We propose the concept of the federated power plant (FPP), a VPP formed through P2P transactions between self-organising prosumers. First, we review existing strategies for coordinating DERs into VPPs, and identify social, institutional and economic issues faced by VPPs. We then review research on P2P energy trading, along with pilot projects under way in several countries, to identify the value-streams P2P transactions offer prosumers and different platform models. Finally, we present a framework for P2P platforms that incentivise prosumers to organise themselves into FPPs, addressing the issues identified with top-down strategies for coordinating VPPs, while offering new transaction opportunities which could improve the efficient allocation of DERs in P2P trading platforms.

Virtual power plant coordination strategies

The strategy used to coordinate DERs into a VPP determines the type of DERs that can be incorporated, their operation and the types of services that can be delivered. Therefore, it has a direct impact on the VPP's capabilities and value.

VPP coordination strategies can be broadly divided into two groups: direct strategies that control individual DERs, and indirect strategies that send incentive signals to influence the consumption/generation decisions of prosumers. These two approaches are described in Box 1.

VPPs that control a large number of DERs can provide grid services, which include transactions in wholesale markets for energy, transmission rights and ancillary services (e.g. reserves, frequency regulation) organised by the transmission system operator (TSO) [11].

Traditionally, distribution network operators (DNOs) have focused on medium and low voltage network planning and reinforcement. It has been recognised that to efficiently integrate DERs, DNOs need to actively manage distribution network power flows, i.e. to transition from network to system operation as distribution system operators (DSOs) [18]. VPPs with awareness of the location of their DERs in a distribution network can provide grid services to DSOs for active distribution network management [19]. In particular, coordinated control of DERs can reduce losses, improve voltage regulation and prevent thermal limits from being violated.

Microgrids can also be operated as VPPs [20]. A microgrid is a cluster of DERs and loads with an electrical boundary, which can operate as part of a power network, or autonomously if islanded [21], [22].

DER coordination requires an underlying communication architecture. Communication architectures can be broadly divided into centralised, where all prosumers communicate with a central coordinator, distributed, with prosumer-to-prosumer communication and unidirectional, with prosumers receiving broadcasts from a coordinator [23]. Both direct VPP coordination and P2P energy trading require either centralised or distributed communication, to accommodate feedback control/negotiation.

Social, institutional and economic issues for VPPs. Social, institutional and economic considerations bring into question the adequacy of existing strategies for coordinating prosumer DERs into VPPs in a number of ways.

Direct control strategies treat DERs as controllable units, potentially working against prosumer preferences for autonomy and control. It is challenging for direct control strategies to provide sufficient flexibility and end-use functionality to appeal to prosumers [15]. An 'opt-out' function can make direct control more acceptable, but this will affect the value of the DER control strategy [15]. In addition, it does not directly address the challenge of identifying new ways in which prosumers may be willing to operate their DERs in a flexible manner. For indirect coordination to provide good performance, the VPP operator faces the significant challenge of understanding and predicting prosumer behaviour [24].

DERs are expected to vary significantly in terms of variability, flexibility, capacity and local network conditions. Prosumers may have individual preferences in terms of financial return, risk-aversion, environmental/social concerns and energy security. Effective DER operation that maximises social welfare requires the VPP operator to obtain all of this information and take it into account. However, current models for VPPs do not necessarily do so and it is often unclear where, and how, learning can take place [25].

While potentially increasing the value extracted from DERs, the incentives for likely VPP operators may be misaligned with those that would yield the best social and environmental outcomes. The electricity market participants that are best placed to implement VPPs are retail suppliers, but they may not be incentivised to organise for socially optimal levels of DER participation, since DERs typically act as competition for the supply of energy and could erode their share of economic rents [26]. Incumbents could also use their 'first mover' advantage to block progress by new entrants, such as information technology firms, which might otherwise have a comparative advantage due to the importance of communications and data processing to VPP operation.

Peer-to-peer energy trading platform value-streams

Markets amenable to P2P trading are characterised by demand variability/diversity and low production economies of scale [27]. These conditions have emerged in power networks with the rise of prosumers

P2P trading platforms have emerged in a range of sectors, reducing transaction costs and allowing small suppliers to compete with large traditional suppliers. Whereas vertically integrated firms take control of the interactions between producers and consumers, P2P trading platforms enable direct transactions between users, with the users in control of setting the terms of transactions and delivering goods and services [17]. Box 2 describes several distinct models for P2P energy trading platforms.

Transactions between prosumers offer the most value when they have complementary resources and/or preferences. P2P energy trading platforms offer three distinct value-streams: energy matching, uncertainty reduction and preference satisfaction.

Energy matching. Coordinated use of complementary DERs could increase total welfare, by reducing upstream generation and transmission requirements and reducing losses. In particular, properly scheduled storage systems and flexible loads can increase the local utilisation of variable renewable sources [28].

However, retail electricity contracts meter prosumers individually, so they are only incentivised to shift their own demand to reduce their energy costs [29]. This leads to inefficient utilisation of DERs, and prosumers do not fully benefit from the value of their DERs as a source of capacity.

Load and renewable generation variability mean that active coordination is required to schedule storage systems and flexible loads to minimise upstream capacity requirements [30]. DERs owned by a single entity can be scheduled by an energy management system. However, if DERs are owned by different prosumers, an energy management system is not directly applicable, since the prosumers need to be incentivised to operate their DERs in a coordinated manner. This will require a market mechanism which can incorporate the prosumers' individual preferences and resource characteristics. P2P trading platforms can facilitate this by allowing mutually beneficial energy transactions to be negotiated between prosumers with excess energy and those with complementary demands. Energy transactions could consider factors such as DER capacity, flexibility, uncertainty and network location.

Uncertainty reduction. Prosumers can also benefit through P2P informational transactions. Small loads and renewable sources are often highly variable and difficult to predict. Electric load variability is significantly reduced when consumers are considered in aggregate [31].

Generation from a single type of renewable source will be correlated with weather conditions in a given locality. However, aggregated groups of renewable sources have significantly less variability if they are physically dispersed, or include a mix of technologies [32].

In the absence of smart meters, an important function of retail suppliers has been to manage price risks associated with variable load-serving obligations. This has meant that costs associated with managing uncertainty, including capacity investments and reserves, have been shared equally amongst consumers. P2P trading platforms could provide value by allowing prosumers to contract as cooperative groups while sharing information and risk. It has been shown that groups of wind power producers can increase their collective profits by contracting together in wholesale energy markets to share risk [33]. Similarly, prosumers could trade information with one another, and then more effectively contract as a group with their supplier. P2P transactions could account for the contribution made by each prosumer to the group's variability, and their individual preferences in terms of risk-aversion and financial return. For example, medium-scale commercial prosumers may be more willing to be exposed to fluctuating energy prices than residential prosumers. These and other preferences are incorporated in choices made by prosumers in P2P markets.

Preference satisfaction. Traditionally, electricity has been seen as a homogeneous good. The design and operation of power networks have focused on financial and energy security preferences of consumers, along with supply side considerations. More recently, it has been recognised that prosumers have a range of preferences, including preferences related to the environment [34] and their local community [28], [35]. This is also relevant for commercial prosumers with corporate social responsibility obligations.

P2P energy trading platforms offer the new opportunity to account for heterogeneous preferences of individual prosumers. The Piclo and Vandebron platforms allow prosumers to select and track the source of the energy they buy. The Brooklyn Microgrid P2P trading platform aims to allow philanthropic prosumers to donate energy to low-income households.

P2P trading platforms could allow different classes of energy to be traded. Classes could be differentiated based on source/destination attributes which are perceived by prosumers to have value. Fig. 1 shows this concept for three prosumers and three classes, to demonstrate preference satisfaction as a value-stream for P2P energy trading.

As an example, P2P platforms could be used to facilitate renewable energy trading, accounting for the time and location of energy generation, storage and consumption. In the EU and the US, 'green tariffs' have been introduced – retail supply contracts with certificates specifying the percentage from renewable sources [36], [37]. However, these certificates are tradable, and not tied to consumption with respect to location or time of use. This allows a supplier to advertise a 'green product', while buying renewable energy certificates from a generator in a different region, with a different generation profile. To increase consumer trust in green electricity, the European Consumer Organisation has recommended the creation of new transparent mechanisms to track the delivery of renewable energy to end users [36].

Federated power plants

To capture the value offered by VPPs and P2P energy trading platforms, we propose the concept of the FPP, a VPP formed through P2P transactions between self-organising prosumers. As previously argued, unlocking the value offered by aggregation through traditional VPPs requires top-down institutional arrangements. However, such arrangements tend to be incompatible with socially optimal investment outcomes. P2P energy trading platforms offer an alternative bottom-up approach. A natural development for P2P energy trading platforms is to facilitate transactions for grid services, with groups of prosumers on one side operating together as a FPP, and wholesale markets/TSOs, generators, retail suppliers or DSOs on the other. Fig. 2 shows block diagrams for a VPP, a P2P energy trading platform and the proposed FPP concept which combines these structures.

Rather than directly controlling DERs, or sending incentive signals to individual prosumers, the P2P platform provides a market mechanism facilitating mutually beneficial energy transactions between subscribed prosumers. The P2P platform could then identify opportunities for grid services, and advertise these as contracts which groups of prosumers could fulfil. Through the P2P market mechanism, coalitions of prosumers fulfilling these contracts would naturally emerge. A key objective of the P2P market is to provide a transparent mechanism which prosumers can trust to fairly balance their preferences and requirements.

FPP value-streams. For prosumers in a P2P energy trading platform, forming a FPP offers the opportunity to engage in transactions for grid services like a VPP, allowing them to improve the allocation of their DERs. FPPs provide a new participatory business model for forming VPPs, which addresses several key social, institutional and economic issues, including privacy, trust, control, autonomy, predictability and coordination.

Contributing to grid services provides new sources of value for prosumers participating in the P2P platform. There are opportunities for FPPs to enter into grid service contracts with wholesale markets, generators, suppliers and DSOs.

P2P energy trading platforms have three key roles for facilitating energy transactions: helping prosumers identify complementary resources/preferences, establishing prices for transactions and providing awareness and coordination services to execute transactions. To facilitate the organisation of FPPs, P2P platforms have the additional roles of identifying opportunities for upstream grid services and organising contracts for these grid services between groups of prosumers and upstream market participants.

P2P energy trading platforms can facilitate the participation of groups of prosumers in wholesale electricity markets, including markets for energy and ancillary services. Rather than taking top-down control of these interactions, the P2P platform would advertise contracts for grid services that prosumer coalitions could fulfil, and would provide the necessary communications infrastructure. Through P2P energy transactions, the prosumers would form a trading coalition with the correct combination of DERs to fulfil capacity and controllability specifications. Taking wholesale energy trading as an example, renewable sources could provide the bulk energy requirement over a trading interval, while storage systems are used to meet ramp-rate requirements.

P2P informational transactions allow prosumers to reduce uncertainty associated with their loads and renewable sources, while cooperation allows them to share risk. Operating together as a FPP, the prosumers could enter into long term bilateral contracts with generators and suppliers, to obtain more favourable terms than they would be able to negotiate individually. The P2P platform would play a key role, providing monitoring services and mechanisms for prosumers to enter and exit these long-term arrangements.

FPPs could also provide services to DSOs. The ability of prosumers to provide services required by DSOs, such as voltage regulation, is highly dependent on network location and will vary over time as network power flows change. This makes FPPs particularly attractive, since they could be flexibly formed based on individual prosumer characteristics.

Social, institutional and economic arrangements for FPPs. Several features of FPPs help address social, institutional and economic issues limiting the successful implementation of VPPs.

To facilitate the organisation of FPPs, the P2P platform advertises grid service contracts, which prosumers can form trading coalitions to fulfil. Coalition forming is envisaged as being highly automated, undertaken by prosumer energy management systems based on user settings and information from connected DERs. The best mechanisms for incentivising prosumers to provide grid services are the subject of current research. Several mechanisms for forming trading coalitions are possible, including bilateral contract networks [38] and ex-post profit sharing from coalition game theory [33], [39].

For example, in the case of a bilateral contract network, prosumers would trade energy contracts with one another through a P2P platform. Energy contracts would specify a quantity of energy to be delivered during a particular time interval, and could include additional information including network location and variability. Prosumers would buy and sell contracts by considering their energy preferences and contract prices. The P2P platform would need to facilitate a price negotiation process, so that a mutually agreed set of energy transactions naturally emerges. The P2P platform would then advertise contracts for upstream grid services which groups of prosumers could fulfil.

When operating as part of a FPP, each prosumer would retain control over their DERs, and define the energy transactions they are willing and able to take part in. P2P negotiations would then elicit a group of prosumers that can efficiently provide grid services, and prices necessary to incentivise their delivery. The prosumers' individual preferences and resource capabilities would be contained within their energy transaction decisions. An effective VPP needs to elicit this information from prosumers, which will involve cost, and needs to design a computationally feasible control strategy which can account for this information. A P2P energy trading platform can reduce complexity compared with direct VPP coordination, since it removes the need to design a top-down control strategy that can account for prosumers' individual preferences. Unlike an indirect VPP coordination strategy, the P2P platform does not need to predict prosumers' demand elasticities to determine the prices that will generate a desired response.

Unlike traditional VPPs, which require upfront investment and design based on a complicated business case involving multiple electricity market participants, FPPs act as a second stage of development for P2P energy trading platforms. Traditional VPPs provide value by aggregating large numbers of prosumers, so they meet capacity requirements to operate in wholesale electricity markets. The VPP cannot operate if it fails to subscribe a large number of prosumers, and likely needs to negotiate with multiple retail suppliers, DSOs and the TSO. P2P energy trading platforms can provide value even at small scales, by facilitating prosumer-to-prosumer energy transactions. For example, a P2P energy trading platform could start in a local community with a single retail supplier and DSO. As new subscribers join and the platform grows, it can expand its range of services to include FPP operation and to operate at the scale of a traditional VPP. The lack of a minimum size requirement means there are fewer barriers to entry for DER services coordinated by a FPP than by a VPP, and allows for the gradual building of trust and experience. This could have a system-wide benefit by increasing competition for the provision of DER coordination services.

It is important not to neglect the potential challenges of a P2P paradigm which places prosumers in partial control of energy transactions and providing grid services. To what extent can a P2P energy trading market achieve optimal economic benefits for a DER portfolio? How can it be ensured that bilateral energy transactions will not breach the physical constraints of local distribution networks? How can these technologies be designed so that prosumers are motivated to engage with them, and able to gain the skills and knowledge necessary to use them effectively? These challenges, along with the opportunities presented by P2P energy trading platforms, motivate the need for future research.

Key Areas for Future Research

Research is needed in four key areas to realise the potential of the FPP concept.

Identifying complementary prosumer resources and preferences. New methods are required to characterise prosumer resources and preferences, and to identify DER combinations to provide grid services. When prosumers form coalitions to provide these services, a key question is, 'what is the marginal value contributed by each prosumer?' so profits can be fairly divided.

Trust, knowledge and skill development. Future research could also relate to the trustworthiness of different institutional and business arrangements for FPPs, transmission of knowledge for designing and participating in FPPs, relationships between 'experts' and 'lay members' of FPPs, accountability, perceptions of risk and distributional issues.

Market design for P2P energy trading and FPPs. Prosumer DERs are expected to have disparate characteristics in terms of flexibility, variability and capacity. The services that can be provided to DSOs also depend on the network locations of the prosumers. P2P energy trading platforms will require new market mechanisms to allow for transactions accounting for these characteristics. Key considerations for market design are stability, efficiency and expressiveness [40]. Communications and processing requirements also need to be considered for fast time-scale transactions.

Regulatory change. Electricity markets are designed with the goal of providing universal and secure access to affordable energy. If properly coordinated, prosumer DERs have a significant role to play in this, as well as addressing the new goal of transitioning towards emissions-free generation. Regulatory changes will be needed to allow for P2P energy trading and FPPs as new business models emerge.

Changes to DSO regulations have the potential to significantly impact power system operations. When DSO rate of return is linked to network capacity investments, they are not incentivised to facilitate DER adoption and VPP operation. This could be addressed by associating DSO rate of return with network efficiency. However, for DSOs to directly implement VPPs, more significant regulatory changes would be need, since DSOs are often restricted from energy trading due to their status as regulated monopolies [41]. The FPP concept could provide a means for DSOs to organise an impartial market mechanism facilitating prosumer DER coordination. Further investigation is required to understand how regulations can best align DSO, prosumer, social and power system objectives.

Finally, the need for careful evaluation of P2P trading and FPP initiatives over a sustained period of time cannot be overstated, to allow for institutional learning and to understand their wider impact.

Conclusions

Organising prosumer DERs into VPPs has been recognised as key to realising their value to power systems. At the same time, the value that P2P transactions offer prosumers is motivating the bottom-up formation of P2P energy trading platforms. These platforms present the opportunity to use P2P transactions to incentivise prosumers to self-organise into coalitions that can provide grid services. This FPP model helps address certain social, institutional and economic issues faced by top-down strategies for coordinating prosumer DERs into VPPs, while unlocking additional value for P2P energy trading.

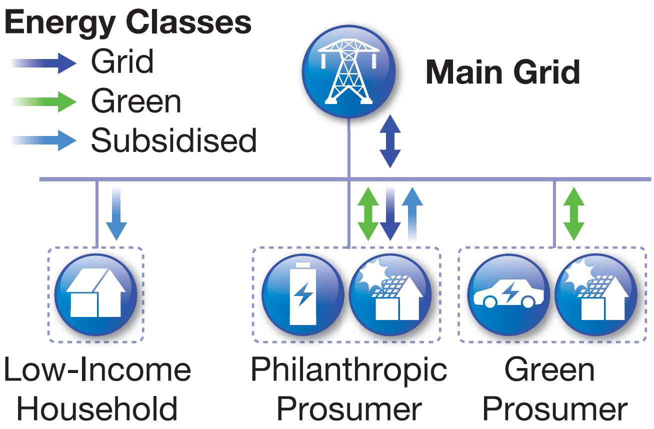


Fig 1| Multi-class P2P energy trading. A stylised example distribution network, where each unit of energy is assigned one of three classes: green energy, subsidised energy or grid energy. The philanthropic prosumer is willing to sell subsidised energy to the low-income household. The green prosumer is able to meet its demand using all-renewable supply by paying a premium for green energy.

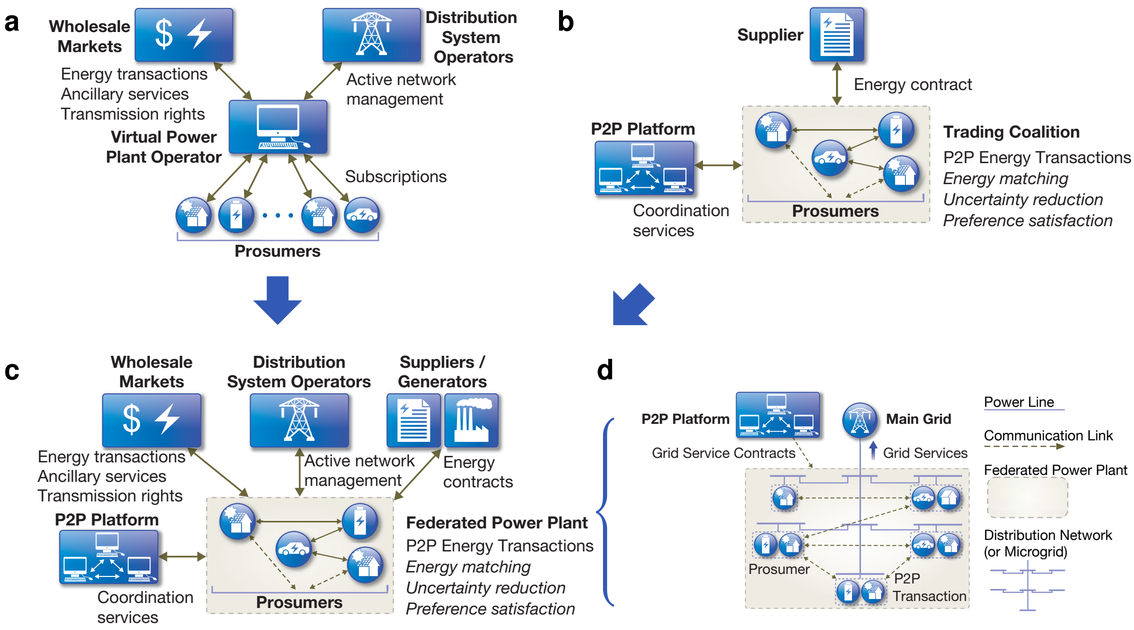


Fig. 2 | Combining the energy transactions of a P2P platform and a VPP. a, VPP operators subscribe downstream prosumers, so they can provide grid services upstream in wholesale markets and to DSOs. **b**, P2P energy trading platforms facilitate energy transactions between prosumers, so they can more effectively utilise their DERs, and contract as a coalition with a retail supplier. **c**, The FPP combines these two concepts. A P2P energy trading platform facilitates transactions between prosumers, and between groups of prosumers on one side, operating together as a FPP, and wholesale markets, generators, suppliers and DSOs on the other. **d**, Interactions within a FPP. The P2P energy trading platform identifies opportunities for grid services and advertises these as contracts to subscribed prosumers. Through the negotiation of P2P energy transactions, the prosumers organise themselves to fulfil the grid service contracts.

Box 1| Strategies for coordinating DERs into VPPs.
The aim of a VPP operator is to aggregate prosumer DERs to provide upstream services to wholesale markets and network operators. VPP coordination strategies can be broadly divided into two groups: **a** direct strategies, and **b** indirect strategies.

Direct DER coordination strategies. DERs under the direct control of a VPP operator (shown in **a**) can be dispatched according to their operating parameters and owners' preferences [11]. Direct control gives the VPP certainty over DER capacity and response, and allows DERs to provide services requiring control at fast time-scales, such as frequency regulation [13].

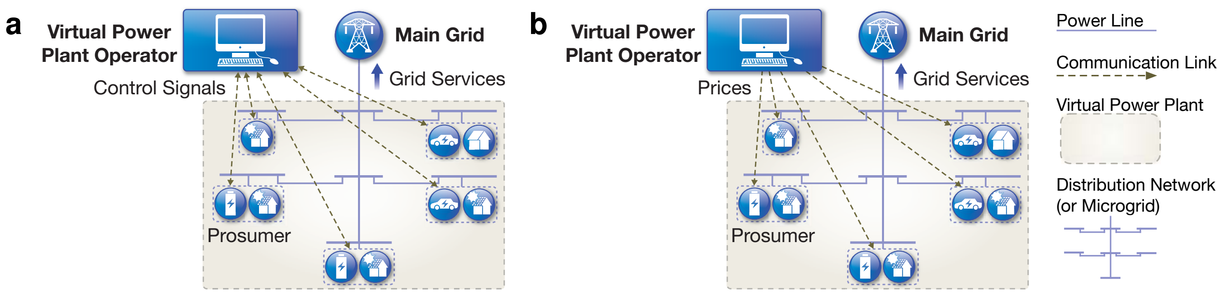
The processing and communications infrastructure required for central control may be impractical for large VPPs. Also, data centralisation introduces privacy and security concerns [42]. To address this, distributed optimisation strategies have been proposed, including Lagrangian Relaxation and Alternating Direction Method of Multipliers [43]–[45]. In particular, strategies based on dual price variable updates can be interpreted as competitive auction mechanisms [44]. However, generally the agent sub-problems are subject to mathematical restrictions (e.g. increasing marginal generation costs, no minimum generation limits), the agents must implement correctly chosen penalty terms and the step-size introduces a trade-off between the number of iterations required to achieve convergence, as well as the accuracy of the obtained solution. Therefore, although these strategies are distributed in terms of communications and processing, they require design and operation by a single entity, and thus are classed as direct.

Indirect DER coordination strategies. Under an indirect coordination strategy (shown in **b**) incentive signals are sent to prosumers. The prosumers then consider the incentives and their individual preferences to make local consumption/generation decisions [14]. Indirect coordination gives prosumers independence over how their flexible loads are scheduled, and can be implemented using unidirectional signals, reducing communication requirements and privacy concerns.

The simplest example of this is time-of-use pricing, which incentivises prosumers to shift loads away from predictable peak demand periods, with the goal of reducing upstream capacity requirements [46]. Day-ahead hourly pricing has also been proposed [47], as well as location-based pricing in distribution networks, to coordinate DERs with respect to their location where clustering of distributed generation and/or new large loads (e.g. electric vehicles, heat pumps) may cause difficulties [48].

Pricing uniformly applied to multiple prosumers runs the risk of causing them to shift their loads to the same low price periods and creating new, possibly worse, demand peaks [43]. Also, indirect price-based coordination strategies can increase demand volatility and reduce system stability [49]. Prices that vary nonlinearly with demand, or are randomly assigned to a subset of prosumers, can prevent new peaks from being created [50]. An intermediate approach between direct and indirect coordination could be for a VPP operator to impose restrictions on the net power demand of subscribed prosumers at particular times, to achieve a desired aggregate response [51].

Indirect coordination strategies are useful when the benefits of direct control are outweighed by the cost of communications and processing infrastructure, or when prosumers are unwilling to grant a VPP operator direct access and control [13], [52].



Box 2| P2P energy trading platform models

P2P energy trading is an emerging field of research, but pilot projects are already under way in several countries, including the Brooklyn Microgrid in the US, Piclo in the UK, Vandenbron in the Netherlands and sonnenCommunity in Germany [16]. Four distinct P2P energy trading platform models can be identified:

Retail supplier platforms. In competitive retail markets, P2P energy trading platforms are a value-added service suppliers can offer to differentiate themselves. Piclo and Vandebron are examples of retail supplier platforms. Allowing prosumers to obtain more value from their DERs should help suppliers retain them as customers. Suppliers can also benefit by gaining better awareness of their customers through their actions in the P2P platform, allowing them to contract more effectively with generators [53].

Vendor platforms. P2P energy trading platforms can also be offered by DER vendors to increase the value of their products. Sonnen, a home battery system vendor, is developing a P2P energy trading platform, sonnenCommunity. P2P energy trading has also been proposed to reduce the charging costs for fleets of electric vehicles [54].

Microgrid/community platforms. P2P energy trading platforms offer a new strategy for incentivising prosumers to support the formation of microgrids and other community energy initiatives. One of the goals of the P2P energy trading platform being developed for the Brooklyn Microgrid is to help coordinate DERs to maintain continuity of supply if the microgrid is separated from the main grid. Community energy initiatives may be based around a shared resource, or shared objectives, such as reducing local pollution [55]. P2P energy trading platforms could be used as part of these initiatives to raise awareness and to incentivise local users to support them. The P2P energy trading pilot projects currently underway are focused on OECD power systems, but another potential application could be incentivising the formation of rural microgrids in developing countries [56].

Public blockchain platforms. Blockchain smart contracts provide a secure decentralised protocol for managing and executing transactions. The Brooklyn Microgrid's P2P energy trading platform uses a centralised blockchain to manage transactions. Public blockchain smart contracts have been proposed to allow P2P energy trading between prosumers without requiring a trusted third party [57]. Several technical challenges still need to be overcome, particularly in terms of privacy and the maximum number of transactions per second. It has also been proposed that wholesale and retail markets could be replaced by a public blockchain platform between prosumers, generators, DSOs and the TSO [58].

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