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Perspective

Multiscale design for system-wide peer-to-peer energy trading

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SUMMARY

The integration of renewable generation and the electrification of heating and transportation are critical for the sustainable energy transition toward net-zero greenhouse gas emissions. These changes require the large-scale adoption of distributed energy resources (DERs). Peer-to-peer (P2P) energy trading has gained attention as a new approach for incentivizing the uptake and coordination of DERs, with advantages for computational scalability, prosumer autonomy, and market competitiveness. However, major unresolved challenges remain for scaling out P2P trading, including enforcing network constraints, managing uncertainty, and mediating transmission and distribution conflicts. Here, we propose a novel multiscale design framework for P2P trading, with inter-platform coordination mechanisms to align local transactions with system-level requirements, and analytical tools to enhance long-term planning and investment decisions by accounting for forecast real-time operation. By integrating P2P trading into planning and operation across spatial and temporal scales, the adoption of large-scale DERs is tenable and can create economic, environmental, and social co-benefits.

INTRODUCTION

Three major components of the sustainable energy transition toward net-zero greenhouse gas emissions are the integration of renewable generation, the electrification of transport, and the electrification of heating.[1] As a result, a significant proportion of future generation and flexibility will be embedded within local distribution networks, in the form of millions of small- and medium-scale distributed energy resources (DERs), including solar and wind generation, home batteries, electric vehicles, and heat pumps.[2] For example, under the International Energy Agency's Sustainable Development Scenario, the share of electricity generation from solar and wind will be 30% in 2030 (from 8% in 2019), electric vehicles will account for 40% of passenger car sales in 2030 (from 2.5% in 2019), and heat pumps will provide approximately 25% of the heating requirements for buildings built between 2019 and 2030.[3]

Given the rapid rate of DER integration necessary for the sustainable energy transition, there is an opportunity for significant additional value to be created by coordinating their planning and operation within distribution networks. Matching renewable generation with flexible demand on a localized basis reduces upstream power flows and losses, and can alleviate the need to curtail excess renewable generation due to distribution network constraints.[4] If DERs can be coordinated on a highly reliable basis, they could also defer or avoid the need for distribution, transmission, and generation infrastructure upgrades.[5] More advanced DER coordination could support additional value streams, such as autonomous microgrid operation to maintain local security of supply during faults,[6] or the provision of flexibility services upstream of the transmission system as a virtual power plant (VPP).[7]

Alongside the rise of DERs, smart meters have seen major roll-outs, providing the infrastructure for secure consumer-level communications and monitoring, and energy management systems are now available that can automate the control of DERs based on owner preferences, resource characteristics, and external price signals.[8] This creates the opportunity for DER owners to actively contribute generation and demand flexibility to the power system. This is described as the consumer-to-prosumer transition (prosumer meaning either "producer-consumer"[9] or "proactive consumer").[10] However, individual prosumers are too small to be directly integrated into existing wholesale electricity markets, which are designed to manage megawatt-scale resources connected to the transmission network. This has motivated the need for new local market mechanisms to incentivize coordination between prosumers and integrate their flexibility into the operation of the power system.[11] Local energy market designs can be broadly divided into three categories: (1) unidirectional pricing, (2) direct dispatch, and (3) peer-to-peer (P2P) energy trading.

The first category, unidirectional pricing, involves price signals that are sent to prosumers using one-way communication, which prosumers then consider when scheduling their flexible energy resources. Time-of-use retail tariffs are a simple example,[12] but more advanced platforms for aggregating demand-side flexibility can also operate on this principle.[13] Coordination can be improved by making prices more granular in terms of time and network location.[14] However, unidirectional pricing has two key limitations. First, good performance requires accurate forecasts and a detailed understanding of prosumer preferences and capabilities, since there is no negotiation process.[15] Second, DERs are coordinated as a group relative to the rest of the system, rather than relative to one another.[16] This is a problem for distribution networks with significant numbers of DERs, since desirable control actions for a particular DER will depend heavily on how other DER owners respond to the price signals they receive.

The second category is direct dispatch. We use this term to encompass strategies whereby prosumers submit bids or DER capability information to a central coordinator, which calculates DER schedules and payments for each prosumer, to provide high levels of controllability.[17,18] Direct dispatch can be used by distribution system operators (DSOs) to create local market platforms for trading energy and flexibility,[19] or by VPP aggregators to manage fleets of DERs.[20] Solving an optimal power flow problem incorporating DER characteristics and network constraints also provides locational prices, which satisfy allocative efficiency, meaning that resources are allocated up to the point at which the marginal benefit of consumption is equal to the marginal cost of generation and transmission.[21] Alternative pricing arrangements have also been proposed, for example, based on fairness criteria[22] or to prevent strategic bidding by prosumer coalitions.[23]

Although direct dispatch has important theoretical advantages, there are a number of challenges for implementation, due to the reliance on a central coordinator. Prosumers need to trust that the central coordinator will operate fairly, despite limited transparency and competition. Computational scalability and privacy are also of concern.[24] Distributed optimization strategies have been proposed to help address these issues,[25] but they introduce significant communication overhead, and although these mechanisms resemble a competitive auction, convergence requires that prosumers act cooperatively, rather than purely pursuing their own individual objectives.[26]

The third category is P2P energy trading, which has been gaining significant academic and industry interest as an alternative market design whereby prosumers negotiate directly with one another.[27] Compared with more centralized approaches, P2P energy trading offers advantages for computational scalability since prosumers retain control over their DERs and negotiate based on individual decision-making.[28] This reduces processing and communications infrastructure requirements and provides greater privacy. Prosumers also have autonomy and can fulfill personal preferences and DER requirements, which might otherwise be difficult to communicate to an intermediary.[29] This is particularly relevant for prosumers with DERs that have a direct impact on their daily lives and comfort, such as electric vehicles and smart heating. Moreover, by providing transparent negotiation protocols by which small- and medium-scale buyers and sellers can reach agreement on mutually acceptable transactions and prices, P2P energy trading can enable greater participation and engagement, thereby increasing market competitiveness.[30]

There is, however, unrealized potential for P2P energy trading to create economic, environmental, and social value if integrated into power system planning and operation across spatial and temporal scales. Early research and trials have focused on P2P energy trading within local distribution networks, but it has been recognized that there are significant unresolved challenges for scaling out P2P energy trading across power systems. In particular, P2P energy trading relies on bilateral negotiation and prosumer-level decisions, making it challenging to (1) enforce network constraints that depend non-linearly on the collective operation of distributed resources,[31] (2) manage aggregated uncertainty without excessive conservativeness,[32] and (3) mediate conflicting requirements between the transmission and distribution levels of the power system.[33] In addition, a major source of unrealized value is the opportunity for P2P energy trading platforms to reduce generation, transmission, and distribution infrastructure requirements. Realizing the full value that P2P energy trading platforms can offer will require new scalable mechanisms for integrating them into how power systems are designed, how investment decisions are made, and how local flexibility is utilized during operation.

In this perspective, we propose a novel multiscale design framework to integrate P2P energy trading as a fundamental component of how power systems are planned and operated. The proposed framework introduces new inter-platform coordination mechanisms to manage the interactions between P2P energy trading platforms and other markets where energy and flexibility are traded at different scales, as well as new analytical tools to improve the efficiency of long-term network planning and investment decisions by integrating the forecast operation of P2P energy trading platforms. This provides a new approach that addresses the unresolved challenges identified for the system-wide scale out of P2P energy trading. The proposed design framework offers new opportunities for value to be created across spatial scales (from local distribution to national transmission) and temporal scales (from seconds-ahead flexibility to years-ahead network planning). The perspective concludes with promising directions for future interdisciplinary research combining power systems engineering, economics, computer science, and social science. We focus specifically on electrical power systems, but the proposed framework could also be relevant for other energy carriers and multicarrier energy systems.

VALUE OF PEER-TO-PEER TRADING ACROSS SCALES

Many academic studies and industry demonstrations of P2P energy trading have focused on the value offered in terms of bill savings for prosumers when trading energy at retail metering timescales (e.g., half-hourly intervals) within a single low-voltage distribution network.[34] This is a reasonable first step for investigating P2P energy trading while it is restricted to small-scale trials. However, there are four main reasons this narrow focus neglects important additional sources of potential value. First, since P2P energy trading influences how prosumers manage their flexible resources, it can create value (as well as costs) for other power system stakeholders, including system operators, generators, retail suppliers, and non-participating consumers. Understanding the impact on other stakeholders is critical for business model development and regulatory reform.[35] Second, depending on how P2P energy trading platforms are designed and used, they could create environmental and social value in addition to economic value.[29] Third, considering trading only within a single distribution network restricts consideration of how a large number of local P2P energy trading platforms could

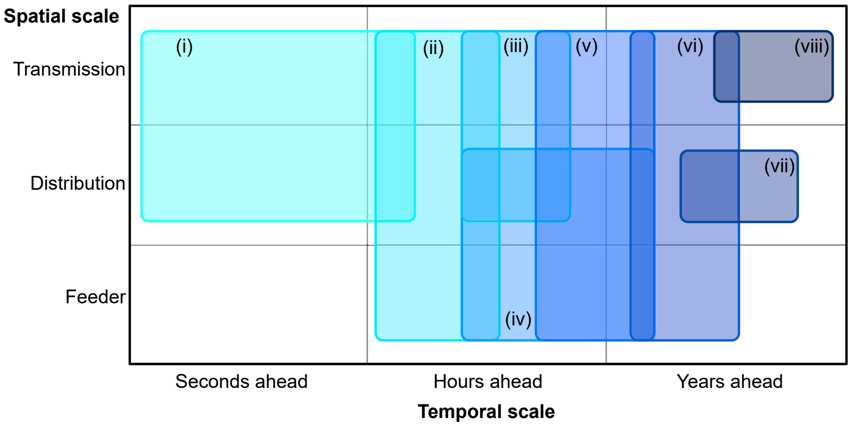

Figure 1. Overview of the potential categories of value that can be created by P2P energy trading, with an indicative mapping to the spatial and temporal scales of integration necessary for them to be realized

(i) Increasing system reliability and preventing blackouts, (ii) reducing renewable curtailment, (iii) reducing losses, (iv) supporting local economies, (v) reducing energy poverty, (vi) incentivizing DER adoption, (vii) deferring distribution upgrades, and (viii) deferring generation and transmission upgrades.

be coordinated to make substantial contributions to overall system operation.[36] Finally, trading at retail metering timescales excludes the value that P2P energy trading platforms could offer for coordinating faster timescale flexibility services, as well as the longer term value created by deferring or avoiding infrastructure upgrades.[37]

Figure 1 presents an overview of different categories of value that could be created by P2P energy trading and an indicative mapping of these to the required scales of integration. These categories are discussed in the following sections.

Increasing system reliability and preventing blackouts

P2P energy trading platforms could be used to enable the bottom-up formation of federated arrangements between coalitions of prosumers to cooperatively provide local power balancing for microgrid formation, or upstream flexibility services.[38] By enabling individual prosumer preferences and capabilities to be accounted for, this could provide a more flexible and technologically neutral alternative to top-down arrangements from individual aggregators.

Reducing renewable curtailment

Matching flexible demand to local renewable generation can alleviate the need for DSOs to directly curtail renewable exports.[32]

Reducing losses

Matching generation and demand within local distribution networks can reduce upstream power flows and losses.[39]

Supporting local economies

P2P energy trading can improve the business case for local clean energy projects, and thereby create jobs and lower energy costs within communities. In addition, prosumers can express personal preferences, such as prioritizing energy from local renewable sources or offering energy at reduced rates to organizations and businesses within their community.[40]

Reducing energy poverty

P2P energy trading can help identify households that face energy poverty by increasing data visibility, and enable direct philanthropy by individuals, as well as assistance by government and community organizations.[29] Longer-term support arrangements may provide greater economic stability.

Incentivizing DER adoption

P2P energy trading can improve the utilization and business case for prosumer-owned DERs and satisfy individual preferences for autonomy and privacy.[41] In addition to power system decarbonization, DER adoption is critical for the decarbonization of transportation and heating[42] and improving air quality in cities.[43]

Deferring distribution upgrades

By enabling local energy matching, P2P energy trading can reduce upstream congestion, which can help defer distribution line and transformer upgrades. P2P energy trading can also enhance active measures used to manage distribution network constraints. For example, prosumers who sell flexibility services to their DSO could hedge their risk of non-delivery by buying energy flexibility contracts from peers.[44] Alternatively, in networks where the DSO imposes capacity constraints on individual prosumers, they could trade unused capacity to constrained peers, which would improve economic efficiency.[45]

Deferring generation and transmission upgrades

Once a significant number of prosumers are operating within local P2P energy trading platforms, there is an opportunity to coordinate these platforms to defer the need for new generation plants and transmission lines.[46] However, this requires mechanisms for integrating the operation of local P2P energy trading platforms into system-level markets for energy and flexibility, and requires transmission system operators (TSOs) to account for this when making long-term investment decisions.

CHALLENGES FOR SCALING OUT PEER-TO-PEER TRADING

Despite significant industry interest and venture capital investment, P2P energy trading has been limited to small-scale trials, preventing much of the potential value from being realized.[47] Three major unresolved challenges can be identified for integrating P2P energy trading platforms into power systems at scale.

First is the challenge of enforcing network constraints through bilateral negotiation. This is difficult without a central coordinator, since power flows and voltages depend non-linearly on the collective operation of prosumers. The large-scale adoption of DERs will make actively managing their impact on network constraints increasingly important.[48,49] Compared with transmission networks, distribution networks are more complex, since they connect thousands of individual consumers and have more non-linear characteristics due to reactive power flows and unbalanced lines.[50] One approach is for P2P energy trading platforms to ignore network constraints, but then for the DSO to resolve constraint violations by actively procuring flexibility through a separate local flexibility market.[51] However, this is inefficient and could create opportunities for strategic gaming if prosumers can trade in both the P2P energy market and the local flexibility market. Another approach is for the DSO to be introduced as a central authority to check the outcomes of P2P negotiation.[31,52] If a constraint violation is identified, transactions leading to the violation would be blocked and the prosumers directed to renegotiate. However, this approach may require many iterations to converge and counteracts the advantages of P2P energy trading in terms of scalability and market transparency.

The second challenge is the difficulty of managing uncertainty within P2P energy trading platforms. These can be separated into internal sources of uncertainty, which are associated with participants, and external sources, which concern the interface between the platform and the wider power system. Internal sources of uncertainty include the weather dependence of renewable generation and the behavior dependence of flexible loads. Since there is always a delay between the negotiation of transactions and real-time operation, the actual load and generation of prosumers will not perfectly match market outcomes. Forcing prosumers to individually hedge against uncertainty will lead to overly conservative operation, due to the limited accuracy of individual level forecasting[53] and the lack of aggregation with other uncorrelated sources of uncertainty.[54] External sources of uncertainty include upstream energy prices and network congestion.[55] These are introduced because of the decoupling between local P2P energy trading platforms and other coordination mechanisms, including system-level markets, as well as local platforms (e.g., VPP aggregation platforms, distribution flexibility markets).

Finally, the third challenge is mediating conflicts between the transmission and the distribution levels of the power system. This also arises due to the decoupling between local P2P energy trading platforms and system-level markets. Directly coordinating prosumer-level transactions at the transmission scale would be computationally infeasible and would have limited value.[56] However, the aggregate operation of P2P energy trading platforms needs to be integrated into system-level operation for effective coordination. Existing P2P energy trading platform designs often treat transmission-level power flows and wholesale market prices as exogenous and independent of local operation.[34] However, this will become invalid as the number of prosumers within P2P energy trading platforms increases. At the same time, for P2P energy trading platforms to be effectively coordinated at the transmission system level, internal details, including local network constraints and prosumer autonomy, need to be accounted for. If TSOs and DSOs plan networks without accounting for the potential for P2P energy trading platforms to unlock embedded flexibility, networks will be overbuilt.[57] This will lead to higher network charges and will reduce the value of the flexibility that P2P energy trading platforms could offer, undermining otherwise valuable business models.

MULTISCALE DESIGN FOR PEER-TO-PEER TRADING

To address these challenges and successfully scale out P2P energy trading across power systems, we propose a novel framework for multiscale design. At the transmission system level, power systems are already managed using a multi-timescale approach, with separate markets for coordinating energy transactions and ancillary services at different temporal resolutions.[58] In many countries with liberalized markets, regulators have also introduced new mechanisms for managing power system investment over longer timescales, including capacity markets and contracts for difference.[59] The introduction of embedded DERs means that power system control now also operates over a vast range of spatial scales, from transmission-level power plants to individual households within distribution feeders. Multiscale design builds upon previous work on multiscale modeling and simulation[60,61] to consider not only how the interactions between different spatial and temporal scales can be understood, but also how new coordination mechanisms can be designed to actively manage them.

An important concept for coordinating multiscale systems is multiresolution nesting.[62] Under a multiresolution nested control architecture, computational complexity is managed by introducing a hierarchy of interconnected controllers that each have different ‘‘boundaries of attention,’’ meaning they manage only subsections of the full system, and different ‘‘resolutions,’’ meaning they understand the system at different levels of precision. Controllers at lower levels of the hierarchy operate at high resolution but with tight boundaries, whereas those at higher levels operate with broader boundaries, but lower resolution. A critical element is for the higher-level controllers to account for both the system under control and the lower-level controllers, which are pursuing local objectives within the system. The higher-level controllers should receive feedback from the lower-level controllers and have the ability to send back control signals to steer local control, since the higher-level controllers have greater awareness of overall system operation.

For power systems, the introduction of local P2P energy trading platforms for DER-level coordination within distribution networks can be seen as a step toward a multiresolution nested architecture. However, there is a need for new mechanisms that can integrate the operation of these local P2P energy trading platforms into the system-wide markets at the transmission level, as well as longer-term processes for network planning and investment decision-making.

To address these gaps, we propose a novel multiscale design framework for P2P energy trading with two new components: (1) coordination mechanisms between markets and platforms where energy and flexibility are traded at different spatial and temporal scales and (2) tools for integrating the operation of P2P energy trading platforms into long-term network planning and investment decisions.

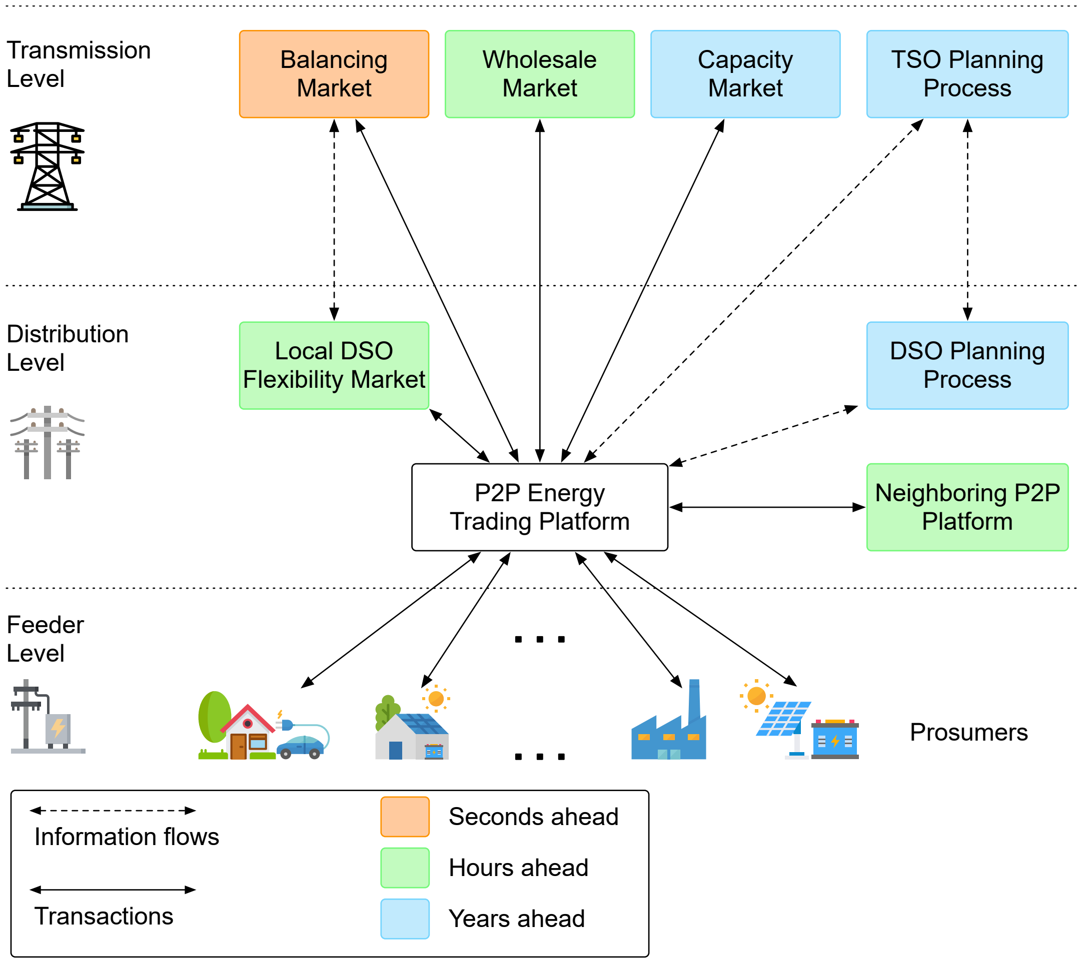

Figure 2. High-level block diagram of interactions between a P2P energy trading platform and other markets and platforms under the multiscale design framework

Boxes identify different markets and platforms operating within the power system. Lines show the transactions (solid) and information flows (dashed) between them. Vertical position indicates the spatial scale at which the markets and platforms operate, and color indicates the main temporal scale at which they operate.

Figure 2 shows a high-level block diagram of the interactions between a P2P energy trading platform and other markets and platforms under the proposed framework, and Table 1 provides a summary of how the features of the proposed framework address the challenges for scaling out P2P energy trading. The subsequent sections discuss these new components in more detail, including trade-offs between different design options and analytical tools that could support their implementation.

Inter-platform coordination mechanisms

The operation of a P2P energy trading platform will have a direct impact on upstream system-level markets for wholesale energy and ancillary services, as well as other local market platforms for flexibility procurement, VPP aggregation, and P2P energy trading, which may operate within the same distribution network or interconnected networks. For inter-platform coordination mechanisms to be scalable, they must introduce at least some level of decoupling between the processing that occurs within separate platforms.[56] We identify three broad potential architectures for new inter-platform coordination mechanisms: (1) bidirectional negotiation, (2) unidirectional pricing, and (3) communication-less predictive coordination. High-level block diagrams for these architectures are shown in Figure 3.

Bidirectional negotiation would involve introducing two-way communication and suitable protocols so that energy transactions between platforms can be agreed upon directly. Relevant mechanisms for bidirectional negotiation that have been proposed for use within P2P energy trading platforms include distributed optimization[63] and bilateral contract networks.[28] Under these approaches, individual market participants reach agreement on a set of mutually beneficial transactions through iterative local decision-making and bidirectional communication. However, these mechanisms are not directly applicable, since in both cases negotiation is synchronous and occurs at a uniform spatial and temporal resolution. For scalability, platform-to-platform negotiation will need to operate asynchronously from intra-platform negotiation and will need to be capable of finding compatible transactions between platforms with different modeling resolutions. This will introduce additional uncertainty on the power flows between the platforms, which needs to be

Table 1. Summary of challenges for scaling out P2P energy trading addressed by the multiscale design framework

	How the proposed framework addresses the challenges	
Challenges	Operational timescale	Planning timescale
Enforcing network constraints without centralization	scalable inter-platform negotiation mechanisms to integrate local P2P energy trading platforms with TSO and DSO flexibility markets	integrates operational forecasts of P2P energy trading platforms into network planning and investment decisions
Managing uncertainty without excessive conservatism	mechanisms allowing an agreed amount of uncertainty to propagate from lower-level platforms to higher-level ones where it can be handled by aggregation and additional sources of flexibility	utilization of granular data from smart meters and substation monitoring to improve forecasts for planning
Mediating transmission and distribution conflicts	a multiresolution nested architecture for inter-platform negotiation across spatial and temporal scales, partially decoupled from intra-platform processing	a multiresolution nested architecture for planning, accounting for inter-relationships between investment and real-time operation

quantified and handled robustly. Negotiation should provide mechanisms that allow an agreed amount of uncertainty to propagate to higher-level platforms with broader boundaries of attention, where it can be handled more easily due to there being a larger aggregation effect and additional sources of flexibility.

Under a unidirectional pricing approach, an upstream platform would set prices (e.g., for energy imports and exports), which would be sent to downstream platforms within its boundaries. This provides scalability, since it requires only unidirectional communication and does not require iterative negotiation. However, the achievable economic efficiency is likely to be lower due to uncertainty associated with how downstream platforms will respond to prices. Upstream platforms that set prices need to ensure they can manage this uncertainty, so it makes sense for higher-level platforms with larger boundaries to be upstream of lower-level platforms. An example of this approach is proposed in Morstyn et al.[32] to manage the interactions between a DSO, which needs to set day-ahead locational import and export prices to manage network constraints, and local P2P energy trading platforms, which enable prosumers to improve the utilization of their DERs by negotiating intra-day transactions with peers. The DSO uses a day-ahead probabilistic dispatch problem to set suitable price gaps between imports and exports, as well as P2P transaction fees, to ensure that network constraints are not violated. This design provides scalability, since the DSO does not need to check and approve the transactions of local P2P energy trading platforms during operation.

The third option is coordination between platforms without communication using predictive modeling. In this case, platform operators would incorporate their predicted impact on neighboring and overlapping platforms into local market clearing. The incorporation of these impacts into clearing processes would be incentivized by a post-operation settlement process between the platforms or, if necessary, enforced by suitable regulatory rules. This approach is potentially the most scalable, since there is no real-time communication, but would require careful design due to the lack of explicit information exchange. Potential approaches for this include model predictive control (MPC)[64] and reinforcement learning.[65] Under an MPC approach, the platform operator would use explicit models of the local platform's impact on neighboring or overlapping platforms for prediction and incorporate this into the market clearing process. The platform would be operated with a receding time horizon, with the predictive models updated based on local measurements. A reinforcement learning approach would operate similarly, but without explicit models of other platforms. Instead, the platform operator would rely on offline training (e.g., in a simulated environment) and learning during operation to understand how it can best manage the local platform, despite uncertainty about the wider system and operation of other platforms.

Finally, there is the potential for hybrid approaches that combine these different architectures. For example, predictive coordination could be used between asynchronous periods of bidirectional negotiation or while waiting for unidirectional price signals to be updated.

Integration into network planning and investment

The three mechanisms for inter-platform coordination presented above fit within the first component of the proposed multiscale design framework, which addresses how P2P energy trading can be more effectively integrated into power system operation. However, the potential value of this will depend heavily on how the power system was designed. For example, in networks with excess generation and transmission capacity, there will be limited value in incentivizing the provision of generation and flexibility from embedded DERs. Conversely, a lack of distribution capacity will prevent local generation and flexibility from being exported upstream. Planning network investments to fully utilize the capabilities of local P2P energy trading platforms is challenging due to the long durations of network upgrade projects, which means that system planners and investors need to make decisions under significant uncertainty. As an example, for ISO New England it can take over 5 years for a 115 kV transmission line to go from planning approval to being in service.[66]

This is the motivation for the second component of our proposed multiscale design framework, namely, the need for new tools to integrate the operation of P2P energy trading platforms into long-term network planning and investment decisions. To address this, we propose the use of bilevel optimization, which provides a structured approach for integrating operational timescale forecasts into power network planning.[67]

Figure 4 shows a high-level block diagram of a bilevel optimization model, which could be applied to integrate the operation of a P2P energy trading platform into TSO or DSO decision-making. In

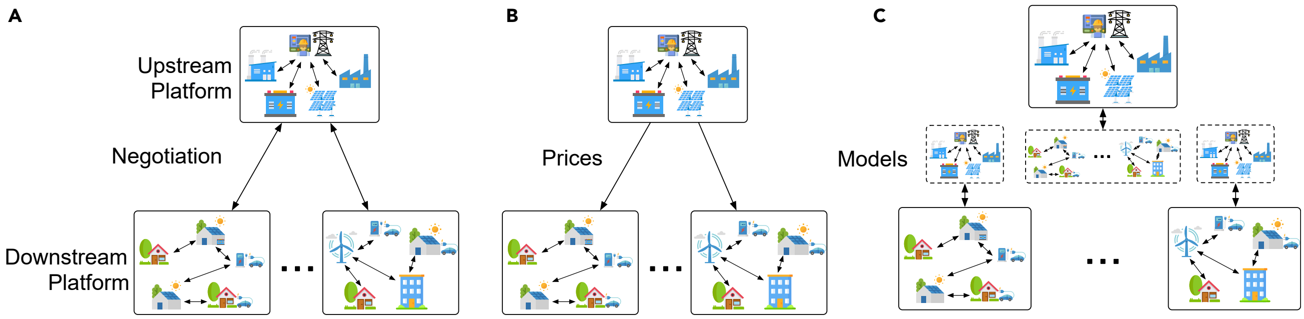

Figure 3. Architectures for negotiation mechanisms between platforms operating at different scales
(A) Bidirectional negotiation, where there is direct negotiation of transactions between platforms operating at different scales.
(B) Unidirectional pricing, where upstream platforms set prices that influence the operation of downstream platforms.
(C) Communication-less predictive coordination, where coordination relies on predictive modeling of neighboring or overlapping platforms.

the upper-level problem, the system operator decides on network upgrades that will maximize its return based on the regulated incentive regime it operates within. The system operator also sets network charges to recover its investment costs and can impose additional incentives or penalties on market participants to achieve policy targets. The decisions from the upper-level problem affect the lower-level problem, which forecasts the DER adoption decisions of prosumers and the P2P transactions and power flows that would occur during operation. The interaction between the upper- and the lower-level problems is two-way, and thus they need to be solved together by the system operator to properly account for P2P energy trading.

Accurate forecasting is likely to be challenging given the rapid rate of change that DER technologies and P2P energy trading platforms are undergoing. However, the large number of international demonstration projects, along with the new availability of granular data from smart meters and substation monitoring, should make this increasingly feasible.[68] An important challenge will be accurately modeling the flexibility that can be procured from prosumers within P2P energy trading platforms, and the uncertainty associated with its delivery, so that this can be incorporated into robust power system planning.[69]

As DERs coordinated by P2P energy trading platforms provide a greater share of overall generation and flexibility, it will become increasingly important to jointly plan transmission and distribution networks.[70] Although network investments are planned long ahead of operation, the combinatorial nature of the problem means that computational complexity remains an important consideration.[71] Introducing constraints to robustly handle uncertainty and to model the inter-relationship between investment and real-time operation will exacerbate this further. Therefore, a multiresolution nested architecture, similar to the approach described for inter-platform negotiation, is also likely to be valuable for planning.

In addition to power system planning, there is a need to incorporate P2P energy trading into the design of the policy mechanisms that are used to guide power system investment.[72] Examples of these mechanisms include capacity markets, contracts for difference, and renewable subsidies. These mechanisms have been introduced in different countries to help achieve specific energy policy objectives, such as decarbonization targets, security requirements, and energy poverty reduction. Ideally, these mechanisms should be designed so that new technologies for DER coordination, including P2P energy trading platforms, can participate and compete with other low-carbon generation and flexibility technologies (e.g., interconnections, grid-scale storage, VPPs) on a level playing field.

CONCLUSIONS AND FUTURE RESEARCH DIRECTIONS

The proposed multiscale design framework provides a new approach by which P2P energy trading can be integrated as a core part of how power systems are designed and operated. The major opportunity is to make DERs more attractive to prosumers and more valuable for system operators, facilitating their successful system-wide scale out. By increasing the adoption rate of DERs and reducing their integration costs, the proposed framework can help accelerate the transition to a decarbonized power system that supplies increasingly electrified transportation and heating sectors. Multiscale design represents a significant shift away from traditional approaches, under which the design of different spatial levels and dynamic timescales relevant for power system coordination are no longer decoupled. Although bringing these different spatial and temporal scales together is challenging, it is also increasingly valuable due to the technological transition to small- and medium-scale embedded DERs with infrastructure for near-real-time sensing, communications, and control. Implementing the proposed framework's integrative approach to network planning and DER coordination will require cooperation between energy market regulators, TSOs, DSOs, and developers of P2P energy trading platforms.

Fully developing and implementing the proposed framework will also require interdisciplinary research bringing together power systems engineering with economics, computer science, and social science. Specific areas related to economics include system operator incentives and regulatory change, areas related to computer science include integrating model- and machine learning-based approaches for coordination as well as information and communications infrastructure, and social science-related areas include prosumer modeling, technology adoption and training, energy justice, and consumer protection.

System operator incentives

The proposed framework describes how system operators can integrate P2P energy trading into investment and operational decisions to create value across different policy dimensions. However, in liberalized markets where system operators are

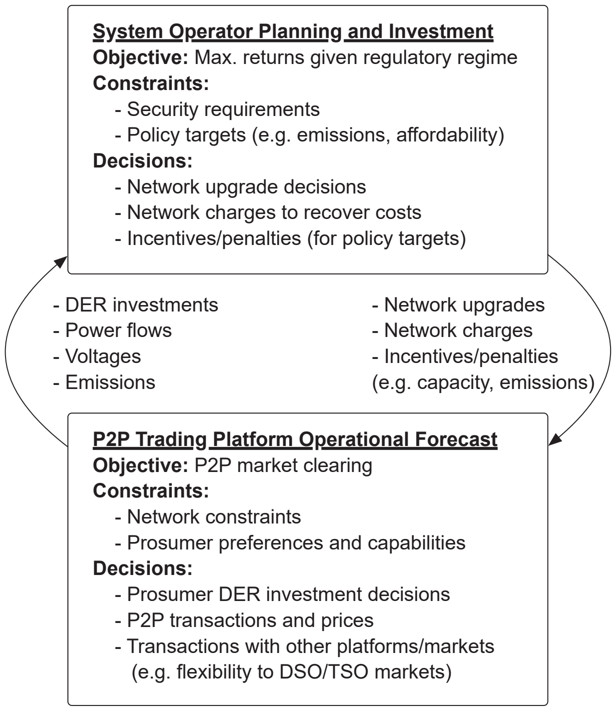

Figure 4. Bilevel optimization approach for integrating the operational forecast of a P2P energy trading platform into system operator planning and investment decisions

The boxes show the objectives, constraints, and decision variables associated with the upper-level investment problem and the resulting lower-level operational forecast of P2P trading. The information flows between the problems couple their solutions together.

structured as regulated monopolies, the market regulator needs to design a suitable incentive regime to ensure this is in the interest of the system operators. Overall cost savings provided by operational expenditures (e.g., DER coordination) and capital expenditures (e.g., network upgrades) should be equally rewarded, and performance targets should encourage innovation.[73] However, setting ambitious but achievable performance targets is difficult because of the rapid rate of technological development and, if set too tightly, may increase the cost of financing.

Regulatory change

Multiscale design provides a new approach for regulators considering the definition of roles and responsibilities associated with P2P energy trading. The details of regulatory reforms will be country specific, but in general, clear rules that retain scope for experimentation and technological change are important enablers of innovation and investment.[74] In addition to system operator incentives, updated regulations are also needed to address how balancing responsibilities are assigned and how network charges are allocated.

Integrating model- and machine learning-based approaches for coordination

There has been significant interest from the power system control community in the potential for machine learning-based approaches to offer lower computational burden and the ability to learn within complex stochastic environments.[75] However, key challenges include the potential for overfitting, which can limit generalizability beyond training scenarios, and difficulty establishing guarantees on performance.[76] A promising direction for developing robust and scalable inter-platform coordination mechanisms could be the combination of machine learning with more established model-based approaches to capture their respective advantages.[77]

Information and communications infrastructure

The selection of sensing, communications, and processing infrastructures used to implement inter-platform coordination will offer a number of important trade-offs. A top-down approach (e.g., with dedicated infrastructure managed by the TSO or strict standards imposed by the regulator) may help with verifying reliability and cybersecurity, but could impose greater costs on participants, entrench incumbents, and limit innovation.[78] Alternatively, coordination mechanisms could be left for platform operators to develop bilaterally, with standards developing based on experimentation. In this case, blockchain smart contracts could provide transparent and trustless transaction protocols.[79] Cost is also an important consideration, with a blockchain-based architecture likely having substantially higher communications, processing, and energy requirements than a cloud-computing-based architecture.[80]

Prosumer modeling

Accurately modeling prosumer behavior within P2P energy trading platforms is critical for successful integration into overall system operation.[81] Critical questions include the following: How much flexibility can be reliably obtained from prosumers? What is the impact of different incentive or penalty mechanisms on the reliable delivery of flexibility? At what level of aggregation can prosumer behavior be accurately forecast? For system planning and network investment decisions, the adoption rate of DERs under different market conditions will also be important. Being able to more accurately model and forecast the behaviors of smaller groups of prosumers will enable P2P energy trading platforms to offer more reliable and localized coordination, opening up new value-streams.

Technology adoption and training

An important area for further research is how P2P energy trading platforms can be designed to make them broadly appealing and easy to use. Preliminary research has indicated there is substantial interest, but that it is concentrated among consumers who are younger, early adopters of technology, and more concerned about climate change.[82] While the details of P2P energy trading platforms developed under the proposed multiscale design framework should be largely invisible to end users, training and organizational change will be necessary for system operators and platform developers, who will each need personnel with skills spanning market design, power engineering, data science, and software development.

Energy justice and consumer protection

Access to affordable and reliable energy is widely held to be a public policy priority, due to its integral role in health and well-being.[83] As P2P energy trading is integrated further into power system operation, the interests of prosumers operating within these platforms, as well as consumers operating outside of them, need to be accounted for. Energy justice provides a social science research framework for investigating where injustices may occur and how these can be avoided or remedied.[84] Energy justice can be divided into distributional justice, which concerns how benefits and costs are allocated throughout society; recognition justice, which addresses how different groups and perspectives are represented and considered; and procedural justice, which focuses on the access of different stakeholders to decision-making and governance processes.[85] Each of these areas is relevant for how P2P energy trading platforms are designed, and where systemic injustices are identified there may be a role for consumer protection regulations.

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AUTHOR CONTRIBUTIONS

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DECLARATION OF INTERESTS

The authors declare no competing interests.

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