Front. Energy
https://doi.org/10.1007/s11708-023-0873-9

PERSPECTIVE

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P2P energy trading via public power networks: Practical challenges, emerging solutions, and the way forward

Abstract Peer-to-peer (P2P) energy trading is an emerging energy supply paradigm where customers with distributed energy resources (DERs) are allowed to directly trade and share electricity with each other. P2P energy trading can facilitate local power and energy balance, thus being a potential way to manage the rapidly increasing number of DERs in net zero transition. It is of great importance to explore P2P energy trading via public power networks, to which most DERs are connected. Despite the extensive research on P2P energy trading, there has been little large-scale commercial deployment in practice across the world. In this paper, the practical challenges of conducting P2P energy trading via public power networks are identified and presented, based on the analysis of a practical Local Virtual Private Networks (LVPNs) case in North Wales, UK. The ongoing efforts and emerging solutions to tackling the challenges are then summarized and critically reviewed. Finally, the way forward for facilitating P2P energy trading via public power networks is proposed.

Keywords distribution network, local virtual private network, network charges, peer-to-peer (P2P) energy trading, practical implementation.

1 Introduction

The paradigm of electric power systems is undergoing a radical change in the course of net zero transition. Conventionally, consumers are usually supplied by the electricity generated by large centralised generators, such as large thermal or hydro power plants. In recent years, distributed energy resources (DERs), such as rooftop solar photovoltaic (PV) panels, battery energy storage systems and electric vehicles, are increasingly connected at the consumer's premises. The DERs change the role of consumers to 'prosumers', which both produce and consume electricity. As a consequence, the power systems paradigm needs to be adapted, in technical, commercial and regulatory aspects, to deal with the surplus electricity of prosumers.

One emerging paradigm for this purpose is 'peer-to-peer (P2P) energy trading', in which prosumers and consumers can directly trade energy with each other [1]. Although called 'trading', P2P energy trading is not merely a commercial arrangement – proper design of P2P energy trading can incentivise the operational flexibility of DERs and facilitate a better local power and energy balance, resulting in a triple-win outcome for prosumers, consumers and power systems [2]. P2P energy trading can be further combined with other strategies for managing DERs. One example is the 'federated power plants' that combine P2P energy trading and virtual power plants (VPPs) for unlocking added value and supporting the economic and secure operation of power systems [3].

P2P energy trading is a rapidly emerging and developing area with a large number of academic studies and industrial trials across the world. According to the survey presented in Ref. [4], there have been an exponentially increasing number of academic papers in this area in the recent few years, and diverse pilots and industrial projects have been planned and conducted in Europe, Asia, and North America. The focus of studies and projects covers a wide range of aspects, including market design, trading platform, infrastructure, policy, and social science perspectives. Managing the strategic behaviors of various parties [5,6], applying artificial intelligence, especially machine learning techniques [7], and considering P2P energy trading from an integrated cyber-physical-social perspective [8] are also important and hot topics attracting a lot of attention. In spite of this, there is still a significant gap between the academic studies or

Received Nov. 28, 2022; accepted Feb. 22, 2023; online May 10, 2023

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Special Column: Microgrids and Integrated Energy Systems

pilots and large-scale commercial deployment of P2P energy trading in practice. As pointed out in Ref. [9], there has been little indication of the implementation of P2P energy trading in the actual energy market in the world.

To achieve P2P energy trading in practice, the electricity exchange agreed between prosumers and consumers needs to be physically delivered through power networks, which could be either private or public power networks[1)]. How to operate private power networks can be wholly decided by the owners on their own, giving a high level of authority and flexibility to the owners. Private power networks also make P2P energy trading a complete 'behind the meter' solution, avoiding the potential issues of various taxes, levies, and charges related to the trading, but usually with a high upfront investment. However, a vast majority of prosumers and consumers are connected through public power networks. Therefore, P2P energy trading through public power networks are critical to its wide implementation in practice, which is the focus of this paper. If implemented properly, P2P energy trading has the potential to address the operational issues (such as over/undervoltage, line congestion, and high network losses) and reduce the peak demand of public power networks, thus reducing the costs for network operation as well as network replacement and reinforcement [2]. These savings will also finally partially pass to end users, resulting in lower electricity bills.

In this paper, the practical challenges of conducting P2P energy trading via public power networks are identified and presented, based on the analysis of a practical case in a county in North Wales, UK. The ongoing efforts and emerging solutions to tackling the challenges are then summarized and critically reviewed. Finally, the way forward for facilitating P2P energy trading via public power networks is proposed. The practical challenges, critical analysis, and the pathway forward presented are original contributions of this paper, and it is hoped that they would be helpful for researchers, practitioners, policy makers, and wider stakeholders to work for scaling up P2P energy trading in practice in the future.

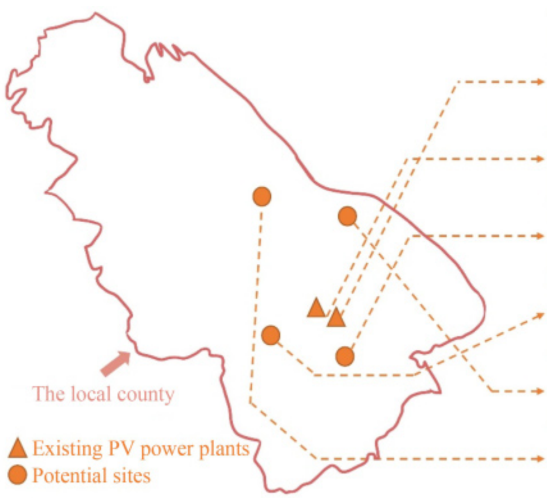
2 Practical challenges

The practical challenges of P2P energy trading via public power networks are identified and analyzed from a practical case in North Wales, UK. The development of this case is still ongoing and has met with various problems and barriers, but the challenges, solutions, lessons, and thoughts obtained from this case so far will be of good practical value and be generalisable to other cases.

This case is located in a county in North Wales of the UK, where there are some local solar PV power plants in operation, as well as several potential sites where PV power plants can be built surrounded by public buildings such as schools, libraries, cemeteries, courts, and office buildings, as shown in Fig. 1.

2.1 Current electricity trading arrangements

Currently in this case, the existing PV power plants and the surrounding public buildings are individually metered and settled with energy suppliers separately. As average



Site name & type	PV generation capacity/MW
Standard Solar Farm (In Operation)	0.65
Brookhill Solar Farm (In Operation)	0.36
Hope Recycling Centre (Potential)	0.5
Theatr Clwyd, Mold (Potential)	2
Broken Bank (Potential)	16.5
Flint Landfill (Potential)	2

Fig. 1 Existing and potential sites of solar PV power plants of this case in North Wales.

1) The companies operating large-scale power networks are 'natural monopolies', and in most countries, they are utility companies regulated by the governments. Therefore, these power networks are called 'public power networks'. By contrast, also in many countries, power customers are allowed to build and operate their own power networks within their properties or also the surrounding small geographical scales with limited network capacity. These networks are owned by private parties, rather than public utility companies, thus referred to as 'private power networks'.

and indicative numbers in April 2019, the public buildings import electricity at £115/MWh, while the local power plants export the generation at only £50/MWh. This fact motivates the local county council to seek direct P2P energy trading between the local PV power plants and public buildings, rather than sell the generation to the energy supplier at a 'low' price while buying electricity back at a much high price.

The major reason for the significantly higher import price than the low export price is that electricity buyers need to pay public power network charges and various taxes and levies along with the wholesale electricity costs [10], while electricity sellers just sell the electricity at the level of wholesale electricity prices plus a few 'embedded benefits' (which refer to payments or benefits that some distribution network connected smaller generators receive [11]), as illustrated in Fig. 2. However, the argument is that, in most of the sites shown in Fig. 1, the PV power plants are only a few kilometres away from the nearby public buildings. Therefore, it is intuitively not fair that all the network charges, taxes, and levies are still needed to be fully paid as if the PV power plants were hundreds of kilometres away from the buildings and as if the electricity were transmitted through a long range of multiple levels of power networks.

2.2 Local virtual private network proposal

In this context, an alternative arrangement, named as 'Local Virtual Private Network (LVPN)' is being sought for the sites. In contrast to building physical private networks, the power generation of the PV power plants is considered to supply the nearby public buildings directly through a virtual route across the public power networks. This is analogous to the widely used 'Virtual Private Network (VPN)' concept in the information technology sector. Accordingly, an appropriate payment needs to be made by public buildings because of the use of public local distribution networks, but many other costs, such as the network charges of transmission and high level distribution networks that are not used, are proposed to be significantly reduced, considering the local power and energy balance among the PV power plants and public buildings.

The LVPN proposal is actually a special case of P2P energy trading, but just with the local generators and demands belonging to the same entity (the local county council in the case). Therefore, the challenges, learnings and discussions of this LVPN case are applicable to other P2P energy trading cases through public power networks.

2.3 Current network charging regulations

The new charging arrangements involved in the LVPN proposal mainly relate to three parts: wholesale costs, network charges, and other taxes, levies and fees (referring to Ref. [10] for the full list of elements). The arrangement on wholesale costs can be largely addressed by the sleeving contracts [12] (with a time resolution, e.g., half-hourly or even smaller), while the taxes, levies and fees need to consider complex historical development, distributional effects and many non-technical factors, which are highly different for different areas and countries. Therefore, this paper focuses on network charges, where the major technical benefit of P2P energy trading, i.e., the local power and energy balancing, can make a difference. Especially, the charges regarding distribution networks, where P2P energy trading happens, are focused on by this paper, which accounts for as much as 14.3% in the electricity bill of all the related assets.

Distribution network charges are the charges for distribution network operators (DNOs) to build, operate, maintain, repair, and invest in the distribution networks. In the UK, they are called 'Distribution Use of System (DUoS)' charges, which are collected by DNOs via energy suppliers for recovering the costs of existing

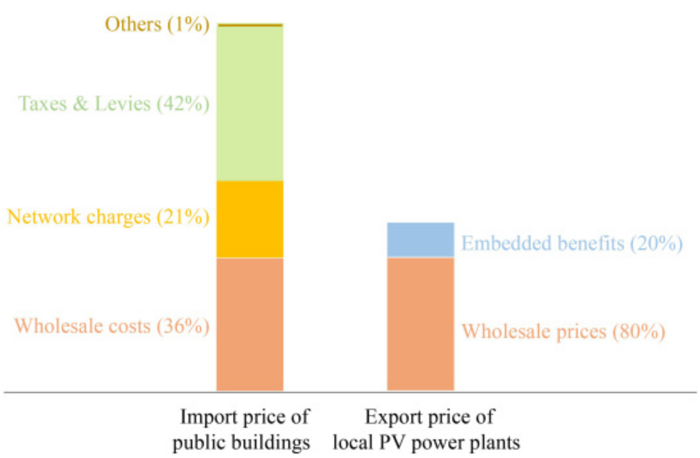


Fig. 2 Indicative electricity import and export prices in the county.

networks and also for building new networks in the future. The DUoS charges consist of multiple components, including unit energy rate (p/kWh), fixed charge (p/d), capacity charge (p/(kVA·d)) and reactive power charge (p/kVarh). The DUoS charges currently applying to most local power plants and public buildings in the local county are calculated by the so called 'Common Distribution Charging Methodology (CDCM)'. CDCM captures and signals both reinforcement and replacement costs of all levels distribution networks below the 'Grid Supply Point (GSP)' (i.e., the transformer dividing electricity transmission and distribution networks) [13].

Under the current regulations, local power plants actually pay negative DUoS charges, i.e., receiving 'generation credits' [14], but intermittent generators, like PV power plants, usually receive a lower level of credits compared to non-intermittent generators [15]. The public buildings pay DUoS charges in the form of a mix of unit rates, fixed charges, capacity charges and reactive power charges [13].

2.4 Problems of current network charging regulations

The analysis and practice of LVPN in the local county found that the current DUoS regulations produce significant barriers for the development of P2P energy trading through public power networks. Specific problems are presented and analyzed as follows.

Problem 1: Not cost-reflective of actual use of networks

The current DUoS regulations are not cost-reflective in several aspects, but those that are closely related to P2P energy trading are just discussed. The customers connected to low and medium voltage distribution networks currently need to pay the costs of the networks of all voltage levels below the GSP. However, the generation from the potential PV plants and the surrounding public demands can be largely balanced locally at the high-voltage level, and only a part of energy exchange needs to go through higher levels of networks. It is estimated that, on average for the four potential sites as shown in Fig. 1, as much as 63% of electricity demand can be supplied by the local PV power plants through low and medium voltage distribution networks (i.e., below 66 kV).

Problem 2: Providing little incentive for local power and energy balancing

In the current DUoS regulations, local PV power plants and demands are metered individually and pay DUoS charges separately. As a result, they are not offered incentive to cooperate with each other for better local power and energy balancing. However, significant planning and operational challenges will be posed on future power networks in the low-carbon transition of the society, because of the intermittency and randomness of increasing distributed renewable power generation and the significant increase and pattern change of electric demand with the electrification of transport and heat sectors.

In this context, it is of great importance to incentivise the flexibility in both local generation and demand as well as energy storage for better local power and energy balancing, which will reduce peak demand/generation, thus postponing the costly network reinforcement, and also improve the operational economy, reliability and security of power networks. The current DUoS regulations fail to provide any incentive in this regard, although there is an argument about whether and to which extent the flexibility should be signaled through DUoS charges or dedicated flexibility contracts [16].

Problem 3: Providing incentive for private power networks

Electric power networks have the economies of scale, scope and density, due to the high sunk costs and low marginal network operating costs, and therefore are natural monopolies in the UK and most other parts of the world. However, this mode has been challenged with the rapidly decreasing costs of distributed renewable power generation and energy storage systems. An increasing number of islanded private power networks are discussed and built across the world, such as islanded mini/micro-grids in remote areas or in places where high power supply reliability is required.

The current DUoS regulations will provide additional incentive for the development of private power networks. If the local PV power plants and demand are connected with each other through private power lines and have only one connection point with the public power networks (i.e., they are behind the same meter), only the net demand (i.e., total demand minus total local generation) will be charged for DUoS, thus leading to a reduced level of DUoS charges overall. The possibilities of building private networks were explored for the sites in the county in North Wales.

However, private power networks might be a lose-lose situation for both the power network operator and customers. For the network operator, private networks will cause duplication of networks and investment and reduce the visibility of part of networks. For the customers who build private networks, they will be faced with high upfront investment, complex contractual and license exemption issues, and long-term uncertainties on investment recovery, supply security and regulatory changes [17]. For wider customers, they will be faced with higher DUoS charges for recovering the sunk costs of existing networks, with fewer customers connected to public power networks. Increased DUoS charges may further encourage more customers to build private power networks, resulting in a vicious cycle (referred to as the 'Death Spiral' for power network companies [18]). Therefore, innovative network charging arrangements are sought for in the LVPN proposal to avoid the problems of building private power networks.

Summarizing the above three problems identified, Problem 1 is about whether a network charging mechanism is able to fairly distribute the investment and operational costs of existing distribution networks among all the prosumers and consumers connected, while Problem 2 is about whether the network charging mechanism is able to provide correct incentive signals so that future replacement and reinforcement of the networks can be reduced or postponed. Problem 3 is somehow a consequence of Problems 1 and 2 – when the existing charging mechanism of public power networks is not fair enough and cannot award the capability of the customers in supporting the networks, the customers may choose to leave the public power networks and build their own private networks to have reduced network costs.

2.5 Ongoing efforts and remaining work

The above problems of current network charging regulations have also been identified by Ofgem, who is the regulator of the gas and electricity markets in the Great Britain. Therefore, in the ongoing 'access and forward-looking charges review' started in December 2018, Ofgem proposed to 'ensure that access and forward-looking charging arrangements reflect where local energy can bring benefits to network management. For example, incentivising users to match generation and demand locally at certain times may make better use of existing capacity, thus avoiding network constraints and the need for expensive reinforcement' [19].

A new arrangement, 'Shared Access', has been proposed and shortlisted by Ofgem in March 2020 [20], which 'allows multiple sites to share access to the whole network, up to a jointly agreed level' [21]. For local generation and demand under Shared Access, there may be a reduction in the upfront network connection charge, or in the ongoing DUoS charges, or both. With this arrangement, local generation and demand conducting P2P energy trading can be put under the umbrella of Shared Access, thus having reduced and more cost-reflective DUoS charges.

However, in the latest consultation published by Ofgem in January 2022, Ofgem decided not to proceed with Shared Access in this round of network charging review [22]. A number of concerns have been identified regarding Shared Access, including practical complexity in terms of metering, control, tariffs, compliance and billing, potential risk of customers being abandoned and then leading to disputes, and the possibility that some benefits of Shared Access may be achieved through other means such as dedicated flexibility contracts. Ofgem is still considering further trialling and testing Shared Access and assessing its value in another "ENA Open Networks" project [23], but this somehow indicates that the Shared Access may not be put into practice in the near term with a clear timeline in the UK.

3 Emerging solutions and remaining issues

The challenges of conducting P2P energy trading through public power networks have been paid attention to by the international research community [24], and a number of studies have been made to propose solutions from different perspectives in the recent two years, as summarized in Table 1.

One category of solutions focuses on the methods to maintain the network operating states within constraints with P2P energy trading, such as the sensitivity analysis-based network permission procedure proposed in Ref. [25], the two-level network constrained scheme in Ref. [30], the line flow constraints-embedded bilateral trading process proposed in Ref. [27], the congestion management model based on market capacity in Ref. [28], and the voltage management scheme proposed in Ref. [29]. Further in Ref. [26], a P2P energy trading scheme that can reduce the peak network demand is proposed, which is able to improve the operational economy as well as deferring the reinforcement of electricity networks. These solutions are important for achieving P2P energy trading through public power networks, but the problems of current regulations presented in Section 3 cannot be addressed by these technology-oriented solutions.

Another category of solutions provides innovative power flow-based network charging mechanisms, which can send cost-reflective price signals, facilitate local power and energy balancing and encourage customers to conduct P2P energy trading through public power networks. A lot of solutions aim at more reasonable network loss allocation among the participants of P2P energy trading, such as the graph-based method in Refs [31,32], current/power tracing-based methods in Refs. [33,34], and other methods considering line losses in Ref. [35]. Cross-subsidisation issues in loss allocation are further addressed in Ref. [36]. However, network losses only account for a very small percentage of electricity bills in the UK, e.g., less than 4% in the bills of the local council assets. Locational marginal pricing mechanisms are proposed in some studies (Refs. [37–40]), which are able to signal wider network-related factors such as congestion in network charges. However, the locational marginal pricing mechanisms, as well as the above loss allocation methods, are all based on power flow or optimal power flow calculation, requiring detailed generation, demand and network data in real time, which are far impractical for low and medium voltage distribution networks in the UK in the near future. Furthermore, the locational marginal pricing and loss allocation methods consider the charges during the operation of networks, while the investment for reinforcement and replacement of networks needs to be embedded into network charges well, which remains

Table 1 Summary and comparison of existing solutions on P2P energy trading through public power networks

Category	Method	Function	Advantage	Disadvantage
Technology-oriented solutions	Sensitivity analysis-based network permission [25]	Tackle both voltage issues and line congestion	Respect network operational constraints and reduce peak network demand for P2P energy trading	Not able to address the problems brought by existing network charging regulations
	Network constrained P2P energy trading [26]			
	Line flow constraints-embedded bilateral trading [27]	Tackle line congestion		
	Market capacity-based congestion management [28]			
	Local information-based voltage management [29]	Tackle voltage issues		
	Grid influenced peer-to-peer energy trading [30]	Reduce peak network demand		
Network-charing solutions	Graph-based network loss allocation [31,32]	Reflect and signal the network losses	Provide the incentive for reducing network losses in P2P energy trading	Network losses only account for a very small percentage of electricity bills
	Current/power tracing-based network loss allocation [33,34]			
	Least-cost energy path optimisation [35]			
	Loss allocation with diminished cross-subsidisation [36]			
	Locational marginal pricing mechanisms [37–40]	Reflect and signal all the major operational network issues including congestion and losses	Provide accurate incentive for reducing network losses and congestion at the same time	Require high-resolution real-time data exchange and do not reflect the network replacement and reinforcement costs
	Exogenous network charging methods [41,42]	Reflect and signal all the long-term and short-term network costs	Simple, good scalability, able to reflect a wide range of costs, and not requiring high network digitalisation level	Oversimplified so being difficult to provide highly reflective and accurate incentive

further research.

There are also some studies proposing simpler exogenous network charging methods for P2P energy trading, specifying the DUoS charges based on electrical distance between the electricity sellers and buyers in the network [41,42] or even simpler principles such as equal sharing in the same zone or globally [42]. Compared to power flow-based network charging methods, exogenous methods require far less information, which are much simpler in terms of computation complexity, and have a good scalability, thus being more practical to be applied in the near term. By contrast, the over-simplified assumptions used in the exogenous methods result in the fact that they are less cost reflective compared to power flow-based methods.

4 Pathway to the future

The barriers faced with the LVPN case in North Wales highlight the necessity of the change of existing network charging arrangements to facilitate P2P energy trading through public power networks. This need is even urgent, considering the rapidly increasing connection of distributed renewable power generation in the context of global efforts in fighting with climate change. Additionally, the challenges and problems identified from the LVPN case in North Wales widely exist in and beyond the UK, given the fact that there has not been a mature network charging mechanism which goes beyond the trialling stage and is ready to be applied to large scale commercial deployment.

As reviewed in the previous section, a number of potential network charging methods, such as locational marginal pricing and graph-based/power tracing loss allocation, have been proposed for fairly reflecting the actual network use and signaling the operational requirements of the network. However, those methods have high requirements on the digitalisation level of distribution networks, which is far not the case for most distribution networks in the world. The methods themselves also need further improvement (e.g., involving the consideration of long-term network reinforcement and replacement) and more trials to collect practical evidence before they could be deployed on a large scale. Therefore, those methods are seen as potential solutions in the long-term.

In the near term, transitional arrangements are urgently needed to better accommodate the many distributed generators already connected to distribution networks and further encourage more investment in distributed renewable power generation. The arrangements need to address the three major problems of the current regulations, becoming more cost reflective, encouraging local power and energy balancing and discouraging private power networks.

One of the most significant difficulties for scaling up P2P energy trading from scratch is that, many potential network benefits (e.g., peak shaving) of P2P energy trading can be achieved only given that most customers in a network (e.g., below the same transformer) participate so that local power and energy balancing can be improved. In other words, the mutual power and energy balancing between just a few customers may not necessarily be directly beneficial for the network. By contrast, in practice, it is difficult to engage most customers in an area all participating in P2P energy trading at one go. Most cases will be like the LVPN case in North Wales – a few customers, who have the willingness and capability, would like to implement P2P energy trading first. However, because no immediate network benefits could be brought by such a small scale of P2P energy trading, how to properly reward and thus incentivise is not clear, leaving an unsolved issue which has been rarely discussed. Therefore, an evolving innovative network charging mechanism needs to be designed to gradually facilitate the development of P2P energy trading from very few participants to covering most customers, and from the immediate near term to the long-term.

The evolving mechanism may involve a dynamic subsidising mechanism, which encourages more customers to participate in P2P energy trading at the initial stage and gradually diminishes when the network benefits gradually grow with the increasing scale of P2P energy trading. The specific network charging methods adopted in the evolving mechanism depend on the development of the digitalisation of distribution networks as well. At the moment, exogenous methods are more practical, while in the future with high digitalisation level, more delicate methods like real-time power flow-based methods can be adopted to send more reflective and accurate incentive signals. Considering the enormous scale of distribution networks, to what extent their digitalisation can reach in the future is still uncertain, and the corresponding cost effectiveness depends on various complicated factors, including the future cost of digitalisation as well as the many potential benefits of the digitalisation besides just P2P energy trading (such as supporting the electrification of heat and transport, improving the resilience against extreme climate).

5 Concluding remarks

P2P energy trading is an emerging and promising energy supply paradigm for managing large amounts of DERs in net zero carbon transition. P2P energy trading has the potential to bring great benefits to both customers and bulk power systems, thus having attracted a lot of attention from the academia and industry all over the world. However, there has been little practical implementation in the real world, especially for public power networks where most DERs are connected.

Based on the analysis of a practical case in North Wales the authors are working on, this paper identified the practical challenges, conducted critical analysis on the emerging solutions, and figured out the pathway forward for implementing P2P energy trading in practice. The key conclusions are summarized as follows.

One key barrier for implementing P2P energy trading in public power networks lies in network charging regulations, since network costs are the most significant electricity bill component where P2P energy trading could bring benefits. The existing network charging regulations have the following three main problems:

- Not cost-reflective of actual use of networks,
- Providing little incentive for local power and energy balancing, and
- Providing incentive for private power networks.

A number of emerging solutions have been proposed accordingly, including technology-oriented solutions which tackle network voltage, congestion and high peak demand issues and new network charging mechanisms reflecting and signaling network losses, operational constraints as well as investment costs.

Nevertheless, these solutions have respective pros and cons, and there is not a 'silver bullet' to addressing all the practical challenges identified. As for the pathway to the future, exogenous network charging methods are more practical for now, while in the future with high digitalisation level, more delicate methods, such real-time power flow-based methods, can be adopted to send more reflective and accurate incentive signals. Furthermore, transitional arrangements, such as a dynamic subsidising mechanism, need to be designed to scale up P2P energy trading from zero, since not enough benefits might be brought by P2P energy trading when its adoption rate is very low.

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