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Contents

Peer-to-Peer Energy Sharing: A Comprehensive Review

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ABSTRACT

As the world is planning for a future with low carbon emissions, today's power system is transitioning from its existing traditional hierarchical structure to a more decentralized framework through innovative energy management techniques, such as peer-to-peer (P2P) sharing. Due to the potential benefits that P2P sharing can offer to electricity prosumers, consumers, and the grid, research, development, and pilot trials of P2P are advancing rapidly. To capture these developments in this emerging energy management paradigm, here we present a comprehensive review of various features of P2P sharing. To do so, first, we introduce the network and market structures that are required to facilitate P2P sharing within a local community. Second, we provide a comprehensive overview of various challenges of

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P2P energy-sharing mechanisms at both virtual and physical layers, followed by a discussion of technical approaches used in literature to address these challenges. Third, we introduce some emerging technological innovations that will be relevant to, and important for, the development of P2P sharing in future markets, and then we discuss how such innovations will advance the state-of-the-art in P2P sharing techniques. Fourth, we provide a summary of existing pilot P2P projects. This is followed by a summary of potential future research directions and a conclusion. Thus, by providing a holistic view of challenges and contributions to both virtual and physical layers of P2P energy systems simultaneously and in a structured way, this monograph delivers a comprehensive understanding of the core challenges that hinder the integration of P2P sharing in the current market model.

1

Introduction

Globally, the demand for electricity is increasing significantly and thus there is a need for more power generation. As a result, environmental pollution from burning fossil fuels is accelerating climate change at an unprecedented pace, as evidenced by recent extreme weather events across the world [71], [81]. As such, several paradigm shifts in power and energy systems are happening to protect the environment, societies, and economies against climate change. One of the key aspects of this rapid transition is the incorporation of distributed energy resources (DER) into power grids [181]. Examples of DER include solar panels, electric vehicles, and batteries. Introducing DER into power systems provides the grid with the flexibility to improve its network performance in terms of reducing voltage fluctuations and increasing network management capacity.

Meanwhile, the sustainability of DER uptake is also contingent on the benefit reaped by prosumers – electricity consumers with DER [111] – at the edge of the grid. For example, prosumers can benefit by reducing their electricity bills by using on-site electricity generation and earn revenue by trading excess electricity in electricity markets [82]. For facilitating prosumers to trade electricity in markets, conventional

approaches include direct method [149], indirect method [111], and feed-in-tariff [212] schemes. In a direct method, an aggregator controls and manages individual DER, and in an indirect method, a designated authority sends a signal to the owners of DER to regulate their dispatch and consumption patterns. In feed-in-tariff, prosumers directly sell their excess electricity to the grid at a price set by the grid. Although these techniques help prosumers to be directly involved in trading electricity and earn revenue, the overall economic benefit is very marginal with limited opportunity for negotiation. As a result, many prosumers have stopped participating in these energy management schemes in some parts of the world [37], [165].

This growing lack of prosumer interest in participating in the electricity market necessitates innovations in developing prosumer-centric [104] energy trading processes and motivates the emergence of peer-to-peer (P2P) sharing. In P2P sharing, a prosumer (also known as a peer) can share electricity with other prosumers in a local electricity market. The key features of P2P sharing include: (1) enabling prosumers to individually decide on energy sharing parameters, such as sharing price and sharing amount, by negotiating with peers involved in a sharing process; (2) no third-party involvement to influence the decisions of participating prosumers during their negotiating process in decentralized P2P sharing; and (3) ensuring secure transactions between participating prosumers and help both the sellers and buyers of energy to obtain more favorable benefits compared to existing approaches. In the last five years, there has been extensive research on and pilot trials of P2P sharing to demonstrate the feasibility of implementations and the potential benefits this technology can offer. As discussed in [183] and [182], the advantages of P2P sharing have been demonstrated in terms of lower electricity bills, reduced carbon emissions, allowing consumers to participate and benefit from P2P sharing, providing demand flexibility to the grid, maintaining network stability in a renewables-dominated grid, and ensuring prosumers' privacy.

However, we are still waiting for the first large-scale implementation of P2P sharing in the electricity market. Although pilot trials have shown potential benefits and implementation possibilities, several yet-to-be-addressed challenges require further research and development.

In this monograph, our purpose is to discuss some of these challenges in light of what has already been implemented, where the gaps are, and what the potential methods are to address these gaps. To do so, we provide the readers with a background of P2P sharing and what kind of projects have been implemented in different countries as pilot trials, before diving into discussions of existing research on both the challenges of decision-making and electricity transferal over P2P networks. We also review some of the emerging technologies with the potential to revolutionize the future of P2P sharing, and we also identify some of the challenges that are critical to address for tailoring P2P sharing schemes from a pilot stage to implementation in real electricity networks.

We note that several review articles on P2P sharing are now available in the literature. Some of these review articles focus on specialized themes including blockchain [18], distributed ledgers [173], local markets [77], [164], and computational approaches [1], [177]. While such topic-specific discussions are very useful for experts in their areas of interest, general readers with a limited understanding of P2P sharing may find them difficult to grasp due to a lack of a deep understanding of such specialized concepts. Other survey articles on P2P sharing in the literature can be classified in terms of studies that discuss the challenges of, and contributions to the virtual layer [182] and the physical layer [46] of P2P networks. Nonetheless, to have a comprehensive understanding of the core challenges that hinder the integration of P2P sharing in current market models, a holistic view of challenges and contributions to both virtual and physical layers is important and should be discussed simultaneously, and in a structured fashion. In that regard, this monograph makes the following contributions:

- We provide an overview of the basics of P2P sharing through a discussion of P2P network structures and P2P market mechanisms.
- We describe how existing studies have contributed to address different challenges relevant to the virtual layer of P2P networks and summarize some key solution concepts that are used to solve selected challenges.

- We review the major challenges that arise due to the P2P sharing of electricity in the physical layer of the power grid and discuss how those challenges are addressed through various technical approaches.
- We review various P2P projects from different countries and continents.
- We identify some key challenges that need to be addressed for a seamless integration of P2P sharing into today's electricity markets, followed by a discussion of selected emerging technologies that have the potential to address some of these challenges.

The rest of the monograph is organized as follows. Some background on P2P networks and market mechanisms is given in Sections 2 and 3 respectively. In Section 4, we review challenges and solution concepts of P2P sharing in the virtual layer that have been addressed in existing studies, and discuss key obstacles that P2P electricity sharing creates in the physical layer and how that is being solved in Section 5. A summary of existing projects implementing P2P sharing is given in Section 6. Some challenges for future research are identified in light of our prior discussion in Section 7 followed by a discussion of some emerging innovative technologies for future P2P sharing solutions in Section 8. Finally, we provide our conclusions in Section 9.

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