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Evaluation of peer-to-peer energy sharing mechanisms based on a multiagent simulation framework☆,☆☆

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HIGHLIGHTS

- A multiagent framework was established to simulate P2P energy sharing.
- Indexes were proposed to evaluate P2P energy sharing mechanisms.
- Heuristic techniques were devised to facilitate convergence of simulation.
- Three existing P2P mechanisms were evaluated in Great Britain context.

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ABSTRACT

Peer-to-peer (P2P) energy sharing involves novel technologies and business models at the demand-side of power systems, which is able to manage the increasing connection of distributed energy resources (DERs). In P2P energy sharing, prosumers directly trade energy with each other to achieve a win-win outcome. From the perspectives of power systems, P2P energy sharing has the potential to facilitate local energy balance and self-sufficiency. A systematic index system was developed to evaluate the performance of various P2P energy sharing mechanisms based on a multiagent-based simulation framework. The simulation framework is composed of three types of agents and three corresponding models. Two techniques, i.e. step length control and learning process involvement, and a last-defence mechanism were proposed to facilitate the convergence of simulation and deal with the divergence. The evaluation indexes include three economic indexes, i.e. value tapping, participation willing and equality, and three technical indexes, i.e. energy balance, power flatness and self-sufficiency. They are normalised and further synthesized to reflect the overall performance. The proposed methods were applied to simulate and evaluate three existing P2P energy sharing mechanisms, i.e. the supply and demand ratio (SDR), mid-market rate (MMR) and bill sharing (BS), for residential customers in current and future scenarios of Great Britain. Simulation results showed that both of the step length control and learning process involvement techniques improve the performance of P2P energy sharing mechanisms with moderate ramping/learning rates. The results also showed that P2P energy sharing has the potential to bring both economic and technical benefits for Great Britain. In terms of the overall performance, the SDR mechanism outperforms all the other mechanisms, and the MMR mechanism has good performance when with moderate PV penetration levels. The BS mechanism performs at the similar level as the conventional paradigm. The conclusion on the mechanism performance is not sensitive to season factors, day types and retail price schemes.

1. Introduction

In recent years, there have been an increasing number of distributed energy resources (DERs) connected to the demand side of power systems. DERs include distributed generators, energy storage systems and flexible demands, and are usually connected to individual houses, buildings, microgrids or distribution networks [1]. The proliferation of DERs pose many challenges, such as reverse power flow and over-voltage issues due to distributed generation, but also bring increasing flexibility contained in energy storage systems and flexible demands

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☆☆ Information on the data underpinning the results presented here, including how to access them, can be found in the Cardiff University data catalogue at http://doi.org/10.17035/d.2018.0046405003.

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[2]. Therefore, there have been increasing interests in investigating how to manage DERs in an optimal way, with a large number of academic literature published and industrial technologies developed.

In the management of DERs, there are mainly two types of entities, i.e. operators and prosumers. The operators refer to either market operators that organise the energy trading between DERs, as well as the related consumers and retailers; or network operators (e.g. distribution network operators, microgrid operators, etc.) that deal with network planning and operation [3]. Prosumers refer to the owners of various DERs, and they are able to generate electricity as well as consume electricity [4]. The research on the management of DERs is categorised into two main streams according to the relationship between operators and prosumers.

In the first category, the operators coordinate all the DERs in a centralized or distributed way to maximise the overall economic benefits or to provide specific types of ancillary services, such as frequency response and voltage support, for power systems [5]. For centralized coordination, direct control is extensively studied and applied to control demand-side resources such as residential and commercial thermostatically controlled loads (TCLs) [6,7], energy storage systems [8] and electric vehicles (EVs) [9]. For distributed coordination, many techniques, such as stochastic pricing [10], Lagrange relaxation (LR) [11] and alternating direction method of multipliers (ADMM)-based optimization [12], are used to obtain a desirable outcome by achieving a convergence (e.g. Nash equilibrium) after an iterative procedure. The objective functions of methods in this category, for both centralized and distributed ones, are mostly to maximise the overall benefits or to achieve certain overall performance of the whole population of DERs, rather than to maximise the benefits of each individual prosumer. Therefore, additional incentives are usually needed to be provided for prosumers to make them participate and allow the intrusive control of their DERs.

In the second category, the operators only provide a local market platform with necessary functions, in which all the prosumers trade or share energy with each other in order to maximise their own benefits individually. Therefore, in this framework, prosumers have full control of their own DERs, and no additional incentives are needed to motivate prosumers to participate. Moreover, reduced computational time and communication infrastructure are required due to its distributed nature [13]. This framework, which is the so-called "peer-to-peer (P2P) energy sharing", is considered in this paper. A number of studies have been conducted in academia on designing proper mechanisms for P2P energy sharing [13–17], and also a rapidly growing number of commercial or pilot projects have been carried out in practice [18–27]. Detailed literature review will be presented in the next section.

Although there are booming research and practices in P2P energy sharing, there is still a lack of systematic methodology to evaluate and compare different P2P energy sharing mechanisms. This issue is of great significance both in academia and industry. A good evaluation method is able to assess the strengths and drawbacks of certain mechanisms, which lights the way for further improvement. In practice, the evaluation method is capable of comparing the performance of several candidate mechanisms, and hence implementing the best mechanism. Although there are a few evaluation indexes scattered in existing studies to assess the performance of P2P energy sharing mechanisms, such as total energy cost and peak-to-average ratio (PAR), there are still significant research gaps:

(1) The performance results derived in the existing studies are usually based on the simulation results with different assumptions of the prosumers' decision-making model. Also, some existing mechanisms do not specify the implementation process. Therefore, a systematic and general simulation framework is needed, which includes all fundamental elements of P2P energy sharing mechanisms and does not rely on specific forms of decision-making or implementation models. The objective of such simulation framework is to make the simulation results (e.g. energy cost of prosumers) under different P2P energy sharing mechanisms comparable to each other in a unified case (e.g. a community microgrid).
(2) More aspects of economic performance remain to be reflected besides the total energy cost. Firstly, the cost saving potential that can be achieved by P2P energy sharing within an area actually has a theoretical upper limit. This upper limit can be used to measure how much potential has been gained and how much more still remains to be explored by adopting a certain P2P energy sharing mechanism. Secondly, an index needs to be defined to show whether the economic benefits obtained by each prosumer are large enough to keep the prosumer staying in the mechanism. Thirdly, it is worth to measure the income inequality among the prosumers in the mechanism besides evaluating the overall cost.
(3) Some existing technical performance indexes need to be extended to assess P2P energy sharing mechanisms. For example, PAR is widely used to reflect the flatness of load curves. However, for a region with many DERs, the maximum loading of the grid transformer may occur when the total load (net load) is negative, so the definition of PAR needs to be extended.

To fill the above research gaps, a systematic methodology was proposed. The main contributions of the paper are presented as follows:

(1) A general multiagent-based framework was established for the first time to simulate the behaviours of prosumers under various P2P energy sharing mechanisms. The framework consists of three types of agents and three corresponding models. Two techniques, i.e. step length control and learning process involvement, were proposed to facilitate the convergence of the mechanism. A last-defence mechanism was established to deal with the divergence. The simulation results are used for calculating the index values for evaluation.
(2) A novel index system was established to evaluate the performance of P2P energy sharing mechanisms. The index system includes three economic indexes (i.e. value tapping, participation willing and income equality) and three technical indexes (i.e. energy balance, power flatness and self-sufficiency). These indexes are normalised and further synthesized into one systemic index to reflect the overall performance.
(3) Three typical existing P2P energy sharing mechanisms were evaluated in current and future scenarios of the power systems in Great Britain (GB). The results verified the effectiveness of the proposed simulation and evaluation methodology, and provided some practical implications on applying P2P energy sharing in the power system in GB.

2. Literature review on P2P energy sharing

This section reviews and comments on existing academic studies and practical projects on P2P energy sharing.

2.1. Academic studies

Some P2P energy sharing mechanisms have been proposed by researchers in the world, although they might have different names in respective studies.

Cintuglu et al. [14] created a competitive market environment for DER owners in a grid-connected microgrid by designing a reverse auction model. In this model, the lumped load is able to be supplied with the lowest cost due to the competitive behaviours of DER owners. A multiagent system was designed and realised at the Florida International University smart grid test system to simulate and verify the proposed model. Three aspects of work remain to be done regarding this study: (1) the consumers were considered as an aggregated agent (rather than individual agents); (2) the decision-making process of energy storage owners was quite simple and heuristic; (3) no flexible