Applied Energy 220 (2018) 1–12

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Peer-to-Peer energy trading in a Microgrid☆

Chenghua Zhang, Jianzhong Wu*, Yue Zhou, Meng Cheng, Chao Long

Cardiff University, Cardiff CF24 3AA, UK

HIGHLIGHTS

- P2P energy trading refers to direct energy trading among prosumers and consumers.
- A P2P system architecture was developed.
- A P2P energy trading platform, Elecbay, was designed.
- P2P energy trading was simulated based on game theory.
- Results prove that P2P energy trading facilitates local power and energy balance.

ARTICLE INFO

Keywords:
Peer-to-Peer energy trading
Distributed Energy Resources (DER)
Bidding system
Game theory
Demand flexibility
Microgrid

ABSTRACT

Peer-to-Peer (P2P) energy trading represents direct energy trading between peers, where energy from small-scale Distributed Energy Resources (DERs) in dwellings, offices, factories, etc, is traded among local energy prosumers and consumers. A hierarchical system architecture model was proposed to identify and categorize the key elements and technologies involved in P2P energy trading. A P2P energy trading platform was designed and P2P energy trading was simulated using game theory. Test results in a LV grid-connected Microgrid show that P2P energy trading is able to improve the local balance of energy generation and consumption. Moreover, the increased diversity of generation and load profiles of peers is able to further facilitate the balance.

1. Introduction

With the increasing connection of Distributed Energy Resources (DERs), traditional energy consumers are becoming prosumers, who can both consume and generate energy [1]. Electricity generation of DERs is usually intermittent and difficult to predict. When prosumers have surplus electricity, they can curtail it, store it with energy storage devices, export it back to the power grid, or sell it to other energy consumers. The direct energy trading among consumers and prosumers is called Peer-to-Peer (P2P) energy trading, which is developed based on the "P2P economy" concept (also known as sharing economy) [2], and is usually implemented within a local electricity distribution system.

A peer in the P2P energy trading refers to one or a group of local energy customers, including generators, consumers and prosumers. The peers buy or sell energy directly with each other without intermediation by conventional energy suppliers [3]. P2P energy trading is usually enabled by Information and Communication Technologies (ICT) -based online services [2].

Conventional energy trading is mainly unidirectional. Electricity is usually transmitted from large-scale generators to consumers over long distances, while the cash flow goes the opposite way. In contrast, the P2P energy trading encourages multidirectional trading within a local geographical area. Trials of energy trading based on the "P2P economy" concept have already been carried out across the globe, for example, Piclo in the UK [4], Vandebron in Netherlands [5], and sonnenCommunity in Germany [6]. These trials mainly focused on providing incentive tariffs to electricity customers from the energy suppliers' perspective.

Piclo is an online platform that performs peer-to-peer energy trading for generators and business consumers. It uses a matching algorithm to match local generation and consumption. Data visualizations and analytics are provided to customers. The meter data, generator pricing and consumer preference information are used to match electricity demand and supply every half hour. Generators have control and visibility over who buys electricity from them. Consumers can select and prioritize from which generators to buy electricity [4].

Vandebron is an online platform in Netherland where energy

☆ Information about the data supporting 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.2018.0046980048.

* Corresponding author.
E-mail address: wuj5@cardiff.ac.uk (J. Wu).

https://doi.org/10.1016/j.apenergy.2018.03.010
Received 21 December 2017; Received in revised form 25 February 2018; Accepted 13 March 2018

consumers can buy electricity directly from independent producers, such as farmers with wind turbines. Similar to Piclo, Vandebron acts as an energy supplier who provides incentive tariffs for consumers and generators to exchange energy. Prosumers who inject surplus energy to Vandebron are able to purchase energy from Vandebron at a lower price compared with other suppliers [5].

SonnenCommunity was developed by SonnenBatterie, which is a battery storage manufacturer in Germany. It is a community of SonnenBatterie owners who share self-produced energy with others with a low-priced tariff provided by SonnenCommunity. With a SonnenBatterie system and photovoltaic panels, members can completely cover their own energy needs on sunny days, and even have surplus energy. This surplus energy is not fed into the power grid, but into battery energy storage that serves the community when they cannot produce sufficient energy due to bad weather [6]. The idea is very similar to those of Piclo and Vandebron, but sonnenCommunity highlights the importance of the storage system.

In recent years, P2P energy trading has also been investigated at the distribution network level. In [7], a paradigm of P2P energy sharing among neighboring Microgrids was proposed for improving the utilization of local DERs and saving the energy bills for all Microgrids. Alam et al. [8] integrated a demand side management system coordinated with P2P energy trading among the households in the smart grid in order to minimize energy cost. In [9], an energy sharing model with price-based demand response was proposed. In [10], a non-cooperative game-theoretical model of the competition between demand response aggregators for selling energy stored in energy storage was illustrated.

The operation of Microgrids and multi-agent energy management systems in liberalized electricity has been widely discussed in recent years. Roche et al. [11] provided a review of several multi-agent systems which were used for grid energy management. A number of concepts and experiments were compared and analysed. In [12], a selection of available models for distributed generation planning and design was presented and analysed in the perspective of gathering their capabilities in an optimization framework to support a paradigm shift in urban energy systems. In [13], a retailing spot market of electric energy was proposed. Its interoperability with other stakeholders in the electric power infrastructure, which was modelled as a cooperating multi-agent system was elaborated. Mashhour et al. [14] presented a novel hourly-ahead profit model for an active distribution company, which had high capacity level of connected Distributed Generators (DGs) that could make selling proposals for the markets in a pool-based system. Besides, a profit-based network reconfiguration methodology for a multi-substation multi-feeder distribution company was also introduced and analysed. Vergados et al. [15] studied the problem of orchestrating the energy prosumers into virtual clusters, in order to participate in the market as a single entity and to reduce the total energy cost through the reduction of the total relative forecasting inaccuracies. In [16], a general framework for implementing a retail energy market based on the Nikaido-Isoda relaxation algorithm was proposed as an electricity market structure with large DERs penetration and demand side management of consumers. By considering the related uncertainties, the DERs were able to maximise their expected payoff or profit by undertaking strategies through the price bidding strategy considering Nash equilibrium. Coelho et al. [17] discussed the major issues and challenges in multi-agent system and smart Microgrids, presented a review of state-of-the-art applications and trends, and suggested future applications with attention to renewable energy resources integration in emerging scenarios, which would be able to decentralise the high complex energy system, allowing users to participate in the system more actively.

The work presented in this paper contains prominent novelty and contributions compared to the above listed literature. First of all, although many of the above listed papers (including [11,13,15–17]) considered liberalized markets in the forms of bilateral contracts, auctions or energy pools, the entities in the markets were all modelled as either generators or consumers. However, prosumers who are able to both generate and consume electricity are an important type of market entities, and they are not supposed to be modelled as pure generators or pure consumers. In this paper, the prosumers were modelled as entities that are able to shift their roles between generators and consumers. As a result, the ways of dealing with the energy trading among the market entities are changed as well. Secondly, in some of the studies mentioned in [17], the multi-agent systems were used for supporting Microgrid operation and management, or for improving supply reliability and stability. Those are different from the P2P energy trading discussed in this paper, in which the major objective of each peer is to maximise its own economic benefits. Thirdly, this paper establishes a four-layer system architecture model for P2P energy trading and proposes an associated bidding system for the P2P energy trading among consumers and prosumers in a grid-connected Microgrid for the first time, both of which were not addressed in existing studies. Last but not the least, this paper also provides more results on the benefits of P2P energy trading, which were not fully investigated in existing literature.

The structure of this paper is summarized as follows. In Section 2, a four-layer system architecture of the P2P energy trading is proposed. Section 3 discusses a business model and the design of an online trading platform 'Elecbay'. It is an example of the possible implementations in the business layer, based on which a P2P energy trading is carried out. In Section 4, game theory and Nash Equilibrium are used to validate how energy is traded among peers within a Microgrid during the bidding process. Case study is presented in Section 5, in which the benefits of using the P2P energy trading are demonstrated. Section 6 concludes the whole paper.

2. Four-layer system architecture of Peer-to-Peer energy trading

A four-layer system architecture is proposed for P2P energy trading, as shown in Fig. 1, to identify and categorize the key elements and technologies involved in P2P energy trading based on the roles they play.

There are three dimensions in the system architecture.

In the first dimension, the key functions involved in P2P energy trading are categorized into four interoperable layers. Each layer is introduced as follows.

The power grid layer consists of all physical components of the power system, including feeders, transformers, smart meters, loads, DERs, etc. These components form the physical electricity distribution network where P2P energy trading is implemented.

The ICT layer consists of communication devices, protocols, applications and information flow. Communication devices refer to sensors, wired/wireless communication connections, routers, switches, servers and various types of computers. Protocols include TCP/IP (Transmission Control Protocol/Internet Protocol), PPP (Point-to-Point Protocol), X2.5, etc. Communication applications can be various, such as information transfer and file exchange. The information flow refers to the senders, the receivers, and the content of each message transferred among communication devices.

The control layer mainly consists of the control functions of the electricity distribution system. Different control strategies are defined in this layer for preserving the quality and reliability of power supply and control the power flow. Voltage control, frequency control and active power control are examples of possible control functions in the control layer.

Business layer determines how electricity is traded among peers and with the third parties. It mainly involves peers, suppliers, distribution system operators (DSOs) and energy market regulators. Various kinds of business models could be developed in this layer to implement different forms of P2P energy trading.

The second dimension of the system architecture is categorized based on the size of the peers participating in P2P energy trading, i.e. premises, Microgrids, Cells, and regions (consisting of multi-Cells).