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Integrating gas energy storage system in a peer-to-peer community energy market for enhanced operation

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ABSTRACT

Increased use of distributed generation technologies such as photovoltaics (PVs) has transformed passive consumers into active prosumers. While prosumers can contribute to emissions reduction efforts by using PV energy, the utilization of these technologies can also bring about several problems in the grid such as congestion and voltage variation. These problems could be mitigated if intermittent energy can be consumed where it is produced or alternatively converted to gas using power-to-gas (P2G) technology. In this regard, a peer-to-peer (P2P) energy market with an integrated gas-energy storage system (GESS) is relevant to enhancing the utilization of locally produced energy. This can also minimize grid congestion and other problems due to reduced import (export) from (to) the grid. GESS consists of a P2G unit, gas storage unit and hydrogen fuel cell unit for storing surplus PV energy in gaseous form. Prosumers and GESS purchase surplus PV energy with proposed P2P market mechanism. It is observed that GESS integration increases the community's economic social welfare and reduces the reliance on the electricity grid.

1. Introduction

As solar photovoltaics (PV) resources are increasing in popularity, many households have transitioned from being consumers to prosumers. This creates many new problems such as line congestion and overvoltage in the electricity grid [1]. Likewise, feed-in-tariffs (*FiT*) have been low in many countries which does not motivate prosumers to feed excess electricity into the grid [2,3]. Recently, *FiT* is regulated at lower price than the retail energy tariff in many places like China, Australia and Korea [4]. A peer-to-peer (P2P) community energy market is a platform where a group of prosumers within the same locality can trade their surplus energy produced from the distributed PV generations. There could be a market operator who manages the P2P trading mechanism and clears the price. A P2P market can also incorporate other distributed energy resources such as energy storage and demand response. In this context, a P2P energy market is relevant in order to share surplus output from solar PV resources between the prosumers at a mutually agreed price rather than selling it at low *FiT* price. Further, integration of a gas-energy storage system (GESS), can leverage solar PV energy usage by storing surplus PV energy. Consequently, it minimizes the import as well as export of energy between the main grid and the community.

Power-to-gas (P2G) technology is evolving, and it has been popular due to its potential to assist in the integration of electricity and gas networks. P2G can convert electrical energy into hydrogen gas with an efficiency of about 80% and further to synthetic methane by leveraging the principles of electrolysis of water [5]. Similarly, hydrogen fuel cell (HFC) technologies can be used to convert hydrogen to electricity with efficiencies in the range of 40–60% [6]. A system with a hydrogen gas storage, P2G and HFC, can behave as a gas-energy storage system. When P2G is scheduled, electricity is being imported from the electricity network to convert the electricity into hydrogen gas, which can then be stored in a tank. Similarly, when HFC is in operation, this stored gas can be discharged to produce electricity, supplying energy to prosumers with a net energy deficit, or other consumers.

In this paper, we have proposed the P2P energy market mechanism with integrated GESS composed of P2G, HFC and hydrogen gas tank within a community. The P2P market operates in one-hour ahead interval as a single-sided auction mechanism. Prosumers, including GESS, bid to buy energy by submitting their willingness-to-pay (WTP) parameters, which indicates their preference to buy energy from the P2P market on one-hour ahead interval. The P2P market allocates the available surplus PV energy to prosumers according to these bids and later unfulfilled demand is met by the electricity grid. Likewise, GESS helps to increase the utilization of surplus PV energy production and hence reduce total import as well as export of electricity for the

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prosumer community. Further, we have also proposed an index to measure the degree of dependence of the P2P community on the electricity grid, termed an Energy Independence Index (EII). EII shall be monitored to assess the effect of GESS integration.

The main contributions of this work are five-fold. First, WTP based price clearing mechanism for trading surplus PV energy has been introduced. Second, GESS is also modelled as a prosumer within the same framework to enhance the PV energy consumption within the community. Third, the proposed model increases the social welfare of the community of prosumers. Fourth, EII has been proposed as a performance index to evaluate the dependence of a community of prosumers on the electricity grid. Lastly, the proposed mechanism helps to reduce the dependency on the electricity grid.

2. Literature review

Integrated operations of multi-energy carriers (electricity, gas and heat) have been the focus of significant research attention in recent years due to increased coupling between different energy carriers, made possible by conversion devices such as P2G, HFC, gas fired electricity generators, steam engine, heat pumps, and electric heaters. Advantages such as cost savings and performance improvements were reported in past works due to co-optimized operation of multi-energy resources [7–9]. Likewise, integrated planning models for multi-energy systems have been studied in references [10–13]. Market interactions of the gas and electricity coupled integrated systems were investigated in references [14–17]. These studies [7–17] focused on co-optimization of the multi-energy carriers at the transmission level which resulted in improved operations.

P2G is considered to have immense potential within energy networks [18], which can be divided into two main categories i.e. Power-to-Hydrogen and Power-to-Methane. P2G has been suggested to have an important role if supplemented by a storage unit for converting excess renewable energies produced by wind farms and PV solar power plants while also helping to reduce carbon emission [19]. Besides having strong potential for P2G application within electricity grids, it could be also utilized in the transportation sector. In [20], the environment and economic feasibilities of hydrogen energy storage is studied where the storage devices were complemented by wind and hydro-electricity resources in the Ontario region. Deployment of gas storage technologies along with the P2G and HFC technologies could reduce carbon emissions. Similarly, the feasibility study of P2G based gas storage system has been studied in [21] under the implementation of various policies in the Swiss power system. It was found out that P2G could be feasible provided that the gas storage capacity is extended. P2G operations have been integrated into the operation of electricity and gas networks by incorporating P2G operation with optimal power flow representations by using two stage optimization [22,23]. In addition to these applications, P2G has been also proposed to produce heat energy from renewable energy resources via H_2 gas storage and power-to-heat [24]. Co-optimization of multi-energy systems [7–17], and the implementation of P2G in gas storages [18–24] have been investigated in various contexts within electricity networks but have yet to be analysed in the context of P2P markets.

With the rise in popularity of the sharing economy in the transportation and housing sectors, similar possibilities have been suggested for electrical energy resources in [25], in which sharing surplus PV energy has major potential. A review on existing P2P market implementation has been presented in [26], which includes models from academia as well as industry. The review paper broadly categorized the P2P market into three major structures i.e. full P2P market, community-based market, and hybrid P2P market. The P2P market mechanisms could use either centralized approach [3] or decentralized approach or both [26]. A decentralized control approach with P2P energy sharing for a DC microgrid has been studied in [27] which resulted in an increase in resiliency of the electricity grid. In [28], a P2P energy market has been developed with enhanced platform having distinction between the classes of energy based on sources/destination of the energy resources. This method gave an added advantage for the prosumers to express a preference for certain types of trading. For example, some prosumers prefer to buy from a renewable energy supplier rather than from the grid. The cost of using the common infrastructure for the P2P network is modelled by exogenous network charges based on electrical distances in [29]. Electric or hybrid electric vehicles can also be considered as a prosumers when they are able to trade energy with each other, and this has been realized in [30] in which blockchain technologies were utilized. Similarly, there are P2P energy trading market implementations using bilateral contracts [31,32]. A supply demand ratio (SDR) has been proposed as the ratio of the total renewable energy supply to the total net demand in a community of prosumers in [3], where energy price is a function of SDR.

Within the existing literature examining P2P markets [3,26–32] the integration of P2G and gas storage technologies has not been studied. Similarly, multi-energy systems studies [7–24] have not considered P2P energy markets in their investigations. Therefore, a P2P energy market with integrated GESS alongside the other prosumers is proposed in this paper to fulfil the existing research gap. GESS is modelled as a prosumer which can also participate in the P2P market that leads to higher utilization of surplus PV energy within the community thereby reducing energy trading with the utility grid.

3. P2P framework of prosumers with integrated GESS

The prosumer community is assumed to have a community market operator (CMO) running the proposed market mechanism as one-hour ahead market model. The CMO has the responsibility to operate the market by clearing the energy price and scheduling energy resources. All the prosumers j submit their demand, generation and bidding parameter to the CMO. Subsequently, the demand curve and willingness-to-pay curve is formulated. The market operator runs the optimization problem which then clears the price while scheduling the energy demand and generation according to the availability of resources and WTP parameters from each consumer (i.e. prosumers who are behaving as consumers). Fig. 1 describes the energy flow between the prosumers.

Assumptions: The following assumptions have been made regarding the P2P energy market and electricity network when formulating the proposed model:

- The primary purpose of the paper is to formulate the WTP-based market mechanism for prosumers including GESS. Therefore, the proposed model uses a simplified electricity network in order to simplify the complex bidirectional electricity flow between CMO, grid and prosumers such that the system is traceable for reasonable size of the community. This electricity network is assumed to be suitable for bidirectional energy flow with negligible energy losses and free from the line congestion. This assumption is common in P2P market literature to focus on market mechanism [3,33].
- The CMO and prosumers shall be able to communicate via communication links such as wide area networks. Some papers have also considered the use of blockchain technologies to have the bookkeeping of the energy trading and payments associated [30]. Yet, the major cost associated with communication and smart metering is the capital cost, which is a fixed cost having negligible effect on the operation costs. Thus, it is customary to neglect the communication costs in P2P literatures as in references [3,31].
- A one-hour ahead PV generation forecast has been used in the model for convenience when solving the one-hour ahead forward market. We acknowledge that PV generation has intermittency associated even at one-hour ahead forecast, for which mitigation measures are needed such as battery energy storage or mechanisms such as reserve and balancing markets. The proposed P2P market mechanism