Energy 135 (2017) 455—465

Contents lists available at ScienceDirect

Energy

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

Sharing demand-side energy resources - A conceptual design

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ARTICLE INFO

Article history:
Received 8 February 2017
Received in revised form
25 May 2017
Accepted 25 June 2017
Available online 27 June 2017

Keywords:
Demand-side energy resources
Sharing economy
Incentive mechanism
Transactive power
Monopoly equilibrium

ABSTRACT

Motivated by the recent boom of the sharing economy, this paper presents a scheme of sharing demand-side energy resources (DERs) among multiple prosumers. Successful sharing must achieve enhanced utilization efficiency of DERs and, in the mean time, ensure voluntary participation of prosumers and a sharing-enabling aggregator. It is also desirable to incentivize the adoption of DERs. To fulfill these goals, we formulate a mathematical program with equilibrium constraints (MPEC) for DER valuation within a sharing community. The aggregator coordinates DER operations in real-time; then it solve this MPEC problem after each billing period. In doing so, the aggregator evaluates two operating costs for each prosumer: the actual cost under coordination and the counter-factual cost if the prosumer independently traded power with the aggregator. We define the difference in these two costs as the coordination surplus, which the aggregator and the prosumer split. Simulation results demonstrate that this sharing procedure effectively achieves the aforementioned goals.

1. Introduction

Demand-side energy resources (DERs) are widely believed to be one of the most indispensable pillars of a sustainable energy future [1], [2]. While markets and infrastructure for electricity generation and transmission evolve relatively slowly, DERs are rapidly growing worldwide in terms of both volume and diversity as a result of technology advancements and policy pursuits. DERs include but are not limited to distributed generation (DG), plug-in electric vehicles (PEVs), distributed energy storages (ES) and responsive loads of heating, ventilating and air conditioning (HVAC). These resources collectively create potential for significantly improving social welfare by reducing carbon footprint, enhancing affordability and accessibility of electricity, and increasing power grid resilience in the long run.

Despite the promising prospect, the rapid growth of DERs has imposed pressing challenges, which, if not addressed in a timely fashion, can turn DERs into a curse rather than a blessing to society. Regions such as California and Hawaii have entered into a critical stage where system penetration of DERs has exceeded five percent of peak load. As a result, traditional business models of utilities are being substantially disrupted; the emerging incentive mechanism, net metering, is also likely to lead to severe economic inefficiency as the number of self-interested DER participants scales up; also, distribution system operations will need additional coordination to ensure safety and reliability as multidirectional and intermittent power flow becomes increasingly prevalent [3].

Addressing these challenges entails efforts from many aspects, including technology advancements, infrastructure planning and policy incentives, etc. Among those paths is redesign of the business model of retailing electricity, which is the focus of this paper. In particular, we investigate a paradigm with adequate monetary incentives so that energy prosumers are encouraged to share DERs with each other by forming local communities under the coordination of an independent aggregator.

Enabling trading electricity among consumers is closely related to the concept of the *sharing economy*, in which people collaboratively share access to goods and services. The market size of the sharing economy has the potential for increasing global revenues from roughly $15 billion in 2015 to $335 billion by 2025, with hoteling and transportation being the pioneering industries [4]. However, compared with sharing shelter or passenger rides, sharing DER has been rare in practice. This is partly because of the regulated nature of the power sector, and partly because of its

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http://dx.doi.org/10.1016/j.energy.2017.06.144

unique complexity: On-demand DER sharing cannot be pairwise transacted but has to be through the distribution network, involving multiple prosumers and intricate valuation of DER. For this reason, sharing-enabling entities (i.e., aggregators) should play a key role in incentivizing prosumer participation and DER adoption, and facilitate multilateral DER coordination and sharing.

Integrating DERs in power systems has been a research hotspot for years. One stream of literature on DERs has focused on assessing their value in the conventional retail context. For example, reference [5] estimated the demand response potential of residential air conditioning to accommodate photovoltaic (PV) power using hourly customer electricity consumption data. Reference [6] evaluated the potential of utilizing coordinated PEV charging to integrate renewable energy. Reference [7] compared the potential of battery storages versus demand response for electricity bill reduction in residential sectors. Reference [8] investigated the benefit of utilizing demand response to accommodate growing fast-charging EV power.

The second stream of literature proposed load controlling strategies involving DERs. Reference [9] proposed a home energy management algorithm for demand response with energy storage and shiftable loads in presence of real-time electricity pricing. In Ref. [10], a power scheduling strategy for aggregated residential thermostatically controlled loads based on a storage-like aggregate model was proposed to arbitrage intraday wholesale electricity market prices. In Ref. [11], an autonomous energy consumption scheduling algorithm for demand response was proposed to mitigate the voltage rise problem caused by high rooftop PV penetration. Reference [12] proposed a stochastic optimization method for scheduling electric power units considering high penetration of PEVs and renewable energy sources. Reference [13] proposed a stochastic power scheduling strategy for a PEV aggregator in electricity market. These papers assumed that DERs are already in place, without considering the DER adoption and gaming behavior of the prosumers. These papers assumed that DERs are already in place, without considering the DER adoption and gaming behavior of the prosumers.

Studies on locally pricing and incentive mechanism design to encourage DER adoption and management are of important value. Addressing this problem, the third stream of literature proposed price-based mechanisms based on competitive distribution markets or variable price signals. Reference [14] evaluated the promotion impact of demand response of smart home consumers on the distributed PV penetration using non-cooperative game theoretical analysis. In Ref. [15], an interactive power dispatching strategy of multiple virtual power plants with renewable energy and demand response resources was proposed. References [16–19] proposed that the aggregator can generate dynamic prices to incentivize customers. Reference [20] proposed a pricing scheme based on customer adaptive energy consumption level to induce demand response. In Refs. [21,22], the authors assumed that there would be a real-time market (or an independent system operator) in the distribution system that can generate real-time electricity prices (or alternatively, day-ahead electricity prices as in Ref. [23]) to incentivize DER adoption. In Ref. [24], an interactive market between the aggregator and the prosumers in the distribution system was designed to incentivize demand response to accommodate renewable resources. Reference [25] adopted Nash bargaining theory to encourage energy trading and benefit sharing between different microgrids in a day-ahead distribution market. Recent work [26] developed stylized models to analyze the equilibrium outcome of sharing energy storage. The aforementioned mechanisms assume that the individual prosumers themselves are responsive to the price signals or they will actively bid in the distribution markets. However, no mature distribution markets have been in place for the current status quo to enable large-scale adoption of these decentralized operating schemes. By comparison, centralized controlling is in general more efficient and is still the primary mechanism for early-stage DER adoption.

To fill the gap between the second and the third research streams, in this work, we propose a new business model design for sharing DER and encouraging DER adoption under a centralized coordination framework. This design, based on measuring prosumers' DER sufficiency, has not been seen in literature to the best of our knowledge. Specifically, we assume that a group of prosumers form a sharing community so that they can share DER with each other rather than individually trade electricity with the utility company (at higher costs). We consider two operating scenarios: 1) In the actual (and optimal) scenario, an aggregator enables DER coordination within the community by solving an ordinary real-time optimal dispatch problem and trades electricity with the utility based on Time-of-Use (TOU) tariffs. 2) The aggregator also evaluates a counter-factual scenario where a particular prosumer would independently participate in the sharing community (without the aggregator's coordination) and the aggregator would exercise monopolistic market power towards him/her. To evaluate the operating cost of each prosumer in the counter-factual scenario, we formulate a mathematical program with equilibrium constraints (MPEC). The difference between the operating costs of these two scenarios is formally defined as coordination surplus in Section 2. The coordination surplus is allocated to the aggregator and prosumers. As a result, all the stakeholders gain non-negative surplus and prosumers do not defect the community. Moreover, the coordination surplus measures a prosumer's DER insufficiency. Prosumers who have more DER tend to be less charged by the aggregator. Our problem setting (i.e. centralized coordination with prosumer participation incentives) is similar to references [27,28]. In Ref. [27], a heuristic reward system is designed for demand response programs based on customers' comfort and actual participation levels; however, it is not clear if the exogenously determined reward levels are sufficient or efficient for the stakeholders. Reference [28] designed a demand response reward system based on a fairness index to encourage customers to increase demand response participation levels; however, the fairness-based reward system may not guarantee efficient DER utilization among the participants. In our proposed sharing-community setting, the incentives to prosumers are endogenized electricity trading prices and coordination surplus, which result in efficient clearing of DERs. Moreover, we explicitly consider incentivizing the aggregator, which is the core enabler of the sharing community.

The contributions of this paper are the following merits of the proposed sharing scheme: 1) The sharing community is viable. The proposed revenue sharing mechanism enables intra-community power trades at clearing prices that correct the locally suboptimal time-of-use rates. The resulting cost performance ensures both the voluntary participation of self-interested prosumers and the profitability of the aggregator. 2) The proposed scheme not only mitigates the impacts of DG on the grid, but also incentivizes the adoption of various DERs.

Section 2 introduces the basic model settings. Section 3 presents the formulation of real-time DER coordination. Section 4 develops the revenue sharing mechanism. Section 5 demonstrates the effectiveness of the sharing scheme by case studies. Section 6 concludes the paper.

2. System settings for DER sharing

Fig. 1 illustrates a typical DER sharing community with multiple power prosumers (hereafter referred to as users). Each user represents an entity in charge of local power consumption and