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Combinatorial auctions for energy storage sharing amongst the households

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ABSTRACT

This paper presents a business model for energy storage trading in a small neighborhood. A region composed of multiple households with a common energy storage system is considered, the capacity of which is shared amongst the households. The households submit bids to an auctioneer to get storage capacity in the shared energy storage system. This paper introduces a combinatorial auction mechanism for such trades to happen. The participants are allowed to bid in single bid format or with combinations of bids called packages. It also presents a novel winner determination solution for combinatorial auctions that uses an evolutionary algorithm by combining the genetic algorithm with particle swarm optimization. Furthermore, the price determination of each trade is also explained. Using MATLAB, performance evaluation and stability tests of the proposed auction technique are performed and presented in this paper.

1. Introduction

In today's world, energy is produced at large centralized energy plants and transported to end clients through complex transportation structures. With the world's energy demand expected to rise, it is unsurprising that substantial effort has been put into replacing macro-grids with local renewable energy sources, leading to increasingly decentralized systems. High levels of renewable energy generation distinguish decentralized systems and create opportunities for increased energy storage (ES) solutions, smart grid applications, and novel business models based on localized energy markets and supply/demand balancing. As a source of flexibility and security, ES is expected to become one of the key enabling technologies to help revolutionize the way we use and manage our energy systems in the future.

Energy Storage appears to have many advantages that help the traditional market sectors of distribution and retail sales of electricity [1]. In general, off-peak electricity is cheaper compared to peak time electricity, energy storage helps the customers to use more off-peak electricity by allowing them to save electricity when prices are low. It plays a key role in stabilizing the electricity market price, freeing the power sector from speculation and volatility [2]. Placing ES at the strategic locations in the distribution network may reduce the need to reinforce the network to cope with peak loading conditions [3]. ES allows a market driven electricity dispatch and increases proactive participation of customers to secure best cost saving schemes in power systems [3].

ES systems can store energy when there is less demand and release the stored energy back during peak demand periods. ES system are seen as huge candidates to mobilize the demand response for residential units. Residential users are mooted to move towards renewable energy sources in the near future, especially for the larger loads due to price uncertainties [4]. Energy storage systems will be the key players in this transition helping residential units to store electricity for future use [5,6]. However, one drawback of ES devices is that they are expensive and require space. Furthermore, use of ES in residential units is limited for the following reasons [78]:

- Installation and maintenance costs of ES are very high and are entirely borne by the users.
- Finite battery capacity makes the storage control decisions time-dependent and difficult to optimize.
- The main purpose of ES is to save electricity, but the storage systems currently have a very high initial costs.

One way of solving the above limitation is to share ES systems among households. From a utilities perspective, a common ES system with an energy storage capacity greater than a single residential unit is a potential solution. Large-scale co-owned energy storage systems have already been considered as viable options for future energy grids [3,9]. Larger battery dimensions regarding power and capacity were found to

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be profitable and resulted in increased revenue [6].

Since the arrival of smart grids, substantial research has been conducted on energy trading. The auction mechanism has been the cornerstone of many applications in both wholesale and retail electric power markets. It is used in smart grid applications not only for trading, but also for management of the demand side, where various incentives are provided to the users for different actions [10]. Similar to economic auctions, the main purpose of electricity auctions is to find the lowest cost between the demand and supply to maximize the economic efficiency.

In recent years, there have been extensive research efforts to understand the potential of common ES devices for residential energy management purposes [7]. In [8], a scheme was presented for shared ES, where the residential units own ES and lease some of the excess storage capacity to a shared facility controller (SFC). For trading purposes, a Vickery auction is used with cost minimization as the main optimal parameter. In [17], the ES auction presented was an online mechanism, which was composed of a series of one-round auctions. Cost minimization was considered as an optimization parameter, which did not guarantee social welfare maximization. In [18], the idea of using common ES systems with multiple self-interested users was presented, where each user could sell energy to the energy storage systems. A Vickery auction mechanism was used as a trading tool, which did not provide optimal social welfare. In [19], the authors investigated ES ownership sharing between domestic customers and a local network operator in response to the change of energy prices and the distribution network's conditions. However, the method of calculating the total shared capacity and price of trading was not explained. The authors of [20] proposed auction-based allocation of shared ES resources by using periodically organized auctions, which is similar to the work presented here. The authors in [55] present a common energy storage idea for renewable energy producers explaining the problem the end user's side. In [58], an idea of using shared energy storage to decide whether or not to buy electricity from the grid based on ToU is presented [59]. presents the idea where energy storage is shared amongst the costumers buying electricity from the grid but no platform regarding sharing via a competition is presented. Whereas [57] explains the overall benefits of having a common energy storage system rather than individual systems in a prosumer neighborhood. Isolated energy storage systems are not economically viable and for sharing based energy storage system, sizing plays a key role [21]. In [22,23]; a stochastic sizing approach for residential storage units is presented while also showing that energy storage system for residential units are more beneficial in shared or common energy storage scenarios. In [24] the authors introduced a bilevel formulation to optimize the size and location of storage system by introducing rate of return constraint which out-performs the exact methods in terms of solution quality. The main limitation of the above-mentioned work is the failure to recognize that bidders care in complex ways; that is, they are willing to win more than one bid at a time. This problem is also called the exposure problem. Exposure problem is when bidder aims to win several units of one item and end up winning too few because of the competition or when the bidders aim to win more than one item but wins only one and not the pair or set [11]. Several economists have argued that exposure problem should be avoided in auction scenarios as it leads to an inefficient auction outcomes of the auctions and lower revenues [11,12]. A potential solution for which is a combinatorial auction. Combinatorial auctions allow bidders to bid on combinations of items that are available for auction, called packages, rather than individual items [13]. They have demonstrated to solve the exposure problem using the feature of package bidding [12–14].

In this study, a business model is presented in which a common energy storage system is shared amongst various households in a community using auction mechanism. Combinatorial auction mechanism is used as the trading tool. The winner determination problem of combinatorial auctions is considered as NP-Hard [15]. Being a combinatorial optimization problem, the search space is larger than for other optimization problems. Evolutionary algorithms (EA) have been successfully applied in most combinatorial optimization problems. Moreover, the ability of EA to manipulate a group of solutions simultaneously increases the potential for dynamic problems [16]. The GA was inspired by Darwin's theory of evolution [25]. It can be defined as a class of evolutionary algorithms that uses techniques inspired by evolutionary biology such as inheritance, mutation, selection, and crossover. The PSO was originally proposed by Kennedy and Eberhart in 1995 [26], where the social behavior and movement dynamics of insects, birds, and fish were the main inspiration. The PSO algorithm is derived from a simplified social model that is closely linked to swarming theory [27]. A good comparison between PSO and GA can be found in [28], in which the authors proved that the difference in computational cost between PSO and the GA is problem-dependent. The authors of [29] also concluded that the PSO outperforms the GA in terms of computational cost when used to solve unconstrained nonlinear problems with continuous variables and the GA performs better when applied to constrained nonlinear problems with continuous or discrete variables. The GA has been widely applied to solve complex optimization problems because it can control both discrete and continuous variables in addition to nonlinear objective and constrained functions [28]. In contrast, PSO may face problems with constrained optimization problems [29]. However, both the GA and the PSO have strengths and weaknesses; hybridization of the GA and the PSO could lead to further advances, as shown by [27–29]. GA and PSO have been applied to solve the winner determination of combinatorial auctions. In [30]; GA was used to solve the Winner Determination Problem (WDP). The bidders only bid in XOR bid format as GA alone cannot deal with the complexities of OR and AND bid formats while also taking more computational time. In [31]; authors implemented the particle swarm optimization for solving winner determination problem which saturated earlier but with lower optimization value. Winner determination problem of Combinatorial Auctions is similar to 0–1 knapsack problem; and research in WDP algorithms might profit a lot from the algorithms developed for the Multi-Dimensional Knapsack Problem [32]. Hybrid meta-heuristics have been used to solve knapsack problems in the past to solve the issue of optimality and achieve quicker and better results [30–33]

This paper is an extension of [37] with a new application domain. The work done in [37] deals with the combinatorial double auction used for energy trading in between different microgrids. The work presented in this paper deals with the single sided combinatorial auctions instead of what is used to share a common energy storage system amongst multiple households. The main contribution of this study are

- An idea for usage of common energy storage system in a smart community and its allocation based on auction process
- Hybrid evolutionary algorithm based winner determination process for single sided combinatorial auctions
- A novel winner price determination process for combinatorial auctions

The presented auction mechanism is compared with the more commonly used auctions in energy markets and comparisons of different evaluation parameters are also discussed.

The rest of the paper is organized as follows. In Section 2, a brief literature review is presented. Section 3 shows the system model, followed by an explanation of the overall auction process in Section 4. Section 5 presents the simulation study and results. Finally, the paper is concluded in Section 6.

2. System's model

A system composed of n households is considered, such that $n = \{1, \ldots, N\}$. The day is divided into i separate time intervals where $i = \{1, \ldots, b\}$. A household n expects to consume an amount of energy, E_n^i, in