



A robust optimization approach for integrated community energy system in energy and ancillary service markets

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ABSTRACT

Distributed energy resources within local energy systems can be reorganized into a single entity, namely, into an integrated community energy system. This integration provides adequate scale to participate in wholesale markets. This paper proposes a day-ahead scheduling strategy for the integrated community energy system in a joint energy and ancillary service markets. The uncertainty of energy market prices, ancillary service market prices, wind power, and photovoltaic power are taken into account. The proposed integrated community energy system organizes combined cooling, heating, and power systems in different areas, and aggregates diverse distributed energy resources. Meanwhile, regulation up, regulation down, spinning, and non-spinning reserves are simultaneously employed in the proposed model. The robust optimization approach is adopted to handle uncertainty, and confidence intervals of uncertain parameters are predicted by a Gaussian process method. Finally, simulations of a real regional multi-energy system demonstrate the effectiveness and applicability of the proposed model.

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1. Introduction

1.1. Integrated community energy system

Owing to an explosive increase of distributed energy resources, various heterogeneous coalitions have been implemented for energy integration at a local level, such as microgrids [1], virtual power plants (VPPs) [2], community energy systems [3], and combined cooling, heating, and power (CCHP) systems [4]. These local energy systems¹ have the advantages of energy utilization improvement, reliability enhancement and carbon emission reduction [5,6]. Nevertheless, local energy systems are often located in different regions and operated independently. In this regard, unreasonable resource allocation and insufficient flexibility are not negligible.

To address this issue, an integrated community energy system (ICES) has been proposed as an efficient approach to coordinate distributed energy resources and reorganize local energy systems [7,8]. The ICES captures attributes of the above-mentioned local energy systems and applies them to communities. The function of the ICES is not only to ensure energy requirements of local communities, but also to achieve energy exchanges and provide system services to the main grid.

From a development perspective, multi-energy carriers have become a trend in local energy systems [9,10]. The framework of local energy systems regarding multi-energy prosumer (producer–consumer) has been widely investigated in the literature. Xu et al. [11] developed a framework for the ICES to optimize inter-related thermal, gas, and electric power systems. Frameworks of the microgrid [12], the VPP [13], and the residential community energy system [14] have also been proposed to manage coordinated thermal and electrical schedules. A graphical paradigm of a combined distributed energy supply and CCHP system to provide cold/heat/electricity to customers was illustrated in Ref. [15].

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¹ In this context, the heterogeneous coalitions for energy integration at the local level are regarded as local energy systems.

1.2. Energy market and ancillary service market

ICES, as a single entity, has adequate scale to participate in wholesale markets with the integration of distributed energy resources [7]. Whereas scheduling strategy in an energy market (EM) has been extensively researched, the same problem in a joint EM and ancillary service market (ASM) is not that common [16,17].

Regulation, spinning, and non-spinning reserves are generally distinguished in most American ASMs [16]. Among these ancillary services, the spinning reserve represents the first consideration for the local energy system optimization in the joint day-ahead EM and ASM [18–21]. Shi et al. [18] proposed a stochastic bidding strategy for the microgrid, which consists of distributed generation units, renewable generation units, and battery energy storages. Based on the model proposed in Ref. [18], Zamani et al. [19] presented an optimization framework for day-ahead electrical and thermal energy resource scheduling in the VPP. A deterministic optimization algorithm was developed in Ref. [20] for a generation company with an integrated combined heat and power (CHP)-thermal-heat only system. Pousinho et al. [21] focused on the self-scheduling for a coordination of wind power plants with concentrated solar power plants. Meanwhile, optimization research in a joint energy and regulation markets has also been conducted in recent papers [22–24]. Day-ahead stochastic models were proposed in Refs. [22] and [23] for the VPP and the wind-thermal-pumped storage system, respectively. In addition, a scenario-based bidding strategy for a combined wind power and battery storage was presented in Ref. [24].

1.3. Robust optimization approach

The ICES participation in wholesale markets is subject to two main sources of uncertainty: 1) power output of renewable energy resources, and 2) market prices. Robust optimization (RO), which quantifies uncertainty with confidence intervals, has been considered as an alternative approach to stochastic programming for a lower computational burden and a less data dependence [25,26]. Furthermore, the RO approach could not only optimize for the worst realization, but also adjust the level of conservatism by selecting different control parameters [27].

The RO approach has been sensitively employed for different energy system optimization problems. For example, RO models have been proposed to address uncertainty of wind power for unit commitment problem [28] and integrated energy system operation [29]. In addition, the uncertainty of market prices could be modeled via the RO approach, and hence, optimal offering curves were derived for the price-taker producer [30] and the VPP [31]. Taking both renewable power and EM price uncertainty into account, RO approaches were proposed for the CHP-microgrid in Ref. [32] and the VPP in Ref. [33].

1.4. Gaps in the literature and our contributions

Optimal problems of local energy systems participating in the joint EM and ASM are focused on either the spinning reserve or the regulation reserve. To the best of our knowledge, very few works discuss regulation, spinning and non-spinning reserves in a generic framework. Furthermore, the RO approach has not been adopted to address the uncertainty of ASM prices for local energy systems.

Based on the identified research gap, we propose a day-ahead scheduling strategy for the ICES in the joint EM and ASM, with the RO approach to handle the uncertainty of both EM and ASM prices, as well as of wind and photovoltaic power output. The ICES organizes CCHP systems in different areas, and integrates all three types of distributed energy resources: dispatchable generation

units, renewable generation units and storage facilities. Instead of focusing on one type of ancillary service, we incorporate regulation up, regulation down, spinning, and non-spinning reserves into available ancillary services of ICES simultaneously. Moreover, Gaussian process (GP), an effective prediction intervals method, is employed to forecast the confidence intervals of uncertain parameters.

1.5. Paper organization

The rest of this paper is organized as follows. In Section 2, we describe the framework of the ICES and its market operation mechanisms. In Section 3, we provide the model formulation for the ICES in the joint of EM and ASM. In Section 4, we present a case study. Section 5 concludes the paper.

2. ICES framework and its market operation mechanisms

2.1. Framework of the ICES

The ICES is capable of effectively integrating local energy systems through various units, e.g., high-efficiency cogeneration (or trigeneration), renewable energy resources, and storage facilities [7,8]. In view of the fact that CCHP systems have a potential to significantly improve energy efficiency [34,35], in this work, CCHP systems are considered to be the organized local energy systems of ICES. As schematically depicted in Fig. 1, the structure of an CCHP-based ICES energy supply system incorporates four types of units: 1) renewable generation units (wind turbines and photovoltaic arrays), 2) dispatchable generation units (gas turbines and gas boilers), 3) storage facilities (electrical energy storages and thermal energy storages), and 4) energy delivery and transformation units (heat recovery systems, electric chillers, and absorption chillers). In this sense, primary energy sources, including natural gas, electricity, wind, and solar, are transformed into three different energy formats, i.e., electricity, heating, and cooling. We should clarify that, compared to current CCHP systems in Refs. [34,35], we further consider renewable generation units and storage facilities. This complies with a tendency for renewable generation units and storage facilities to be contained in local energy systems [36].

Meanwhile, the ICES can not only exchange energy between organized local energy systems but it can also trade energy with the main grid in wholesale markets [7]. As presented in Fig. 2, electricity, heating, and cooling energy can be exchanged through a radial electricity grid and a ring heating/cooling pipeline network. It should be noted that there is no direct electricity exchange between CCHP systems. The surplus electricity of each area can be sold to the main grid in the EM. Similarly, if energy demands are insufficient, the ICES can purchase electricity from the EM. The operation and control of the ICES are complemented with the applications of smart grid technologies [37]. As such, the economy and reliability of the overall system can be improved by the coordinated optimization of integrated units.

2.2. ICES operations in the EM and ASM

Without the loss of generality, the market structure described in this paper follows California electricity market mechanisms. Since the size of the considered ICES is not large enough, it functions as a price-taker agent in wholesale markets; namely, the behavior of the ICES would not affect the market prices. In addition, as a role of prosumer, the ICES can sell electricity for an hour and purchase it for another hour.

The ICES simultaneously bids in the EM and ASM 1 d in advance.

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