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Multi-party energy management for smart building cluster with PV systems using automatic demand response

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ABSTRACT

In a smart grid environment, the joint operation of multiple Smart Buildings (SBs) could be more advantageous than the independent operation of each individual SB. In order to enable the joint operation, the concept of Smart Building Cluster (SBC) is introduced in this paper. An energy management framework for achieving optimal operations of SBC is proposed, and the information exchange processes between the Smart Building Cluster Operator (SBCO) and the participating SBs are described. A multi-party energy management model for SBC based on non-cooperative game theory is proposed, considering building-integrated PV systems and automatic demand response (ADR), with all participating SBs viewed as players in the game. The existence of Nash equilibrium in the game model is proved, and the process for solving the Nash equilibrium strategy is modeled as a multi-objective optimization problem (MOP). Furthermore, the solution method and procedure based on an iterative method are proposed. Finally, via a practical example, the effectiveness of the model is verified. The proposed method is able to reduce the total cost of the SBs by 4.6% and improve the load factor of the SBC from 0.68 to 0.76 when the proportion of shiftable loads is 25% in the total load profile.

1. Introduction

Power consumption in buildings accounts for approximately 40% of global energy consumption worldwide according to the statistical study [1]. Building energy consumption is heavily dependent on the functionality of the building, the occupants behavior, the outdoor environment, the building materials, and the operational strategy [2]. As a cutting-edge building management technology and an important part of the future smart city concept, Smart Building (SB) features several salient advantages in providing a high level of comfort to customers, minimizing power consumption, and reducing detrimental impacts on the environment [3]. In recent years, the SB technology has attracted more and more attention with the higher penetration of the emerging smart grid technologies.

The SBs utilize modern Information and Communication Technologies (ICT) to manage energy consumption automatically. ICT also plays a crucial role in realizing SBs' Demand Response (DR) function, which is an important feature of demand side management enabled by smart grid technologies [4]. On the other hand, in order to make SBs more environmentally friendly, building-integrated Renewable Energy Sources (RES) such as PV panels are being more commonly utilized [5]. With the purpose of coordinating all the participants in the SBs, an effective Energy Management System (EMS) is highly needed, which is also one of the key technologies in Smart Grid [6–8].

Building Energy Management System (BEMS) enables the power consumer of an SB to automatically perform smart load controls based on utility signals, customer's preferences and load priorities, etc. It has been envisioned that BEMS is able to effectively deal with the conflict between energy consumption and the comfort level in a building environment [9–12]. These studies aimed at achiev-

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Nomenclature

SB	Smart building
SBC	Smart building cluster.
SBCO	Smart building cluster operator
EMS	Energy management system
BEMS	Building energy management system
DR	Demand response
ADR	Automatic demand response
RES	Renewable energy sources
RE	Renewable energy
ICT	Information and communication technologies
PHEVs	Plug-in hybrid electric vehicles
MPP	Maximum power point
MPPT	Maximum power point tracking
RB	Residential SBs
CB	Commercial SBs
OB	Office SBs
TOU	Time-of-use
$\boldsymbol{fl_i}$	The fixed load set of SB i
$\boldsymbol{sl_i}$	The shiftable load set of SB i
$\boldsymbol{P_i}$	The predicted value set of the PV source's active power of SB i
fl_i^h	The fixed load of SB i at period h
sl_i^h	The shiftable load of SB i at period h
$\left[\mathrm{sl}_i^{\min}, \mathrm{sl}_i^{\max}\right]$	The value range of sl_i^h
$\left[\alpha_i, \beta_i\right]$	The optional time range interval of the shiftable load for SB i
P_i^h	The predicted PV source's active power of SB i at period h
NL_i^h	The net load of SB i at period h
NL_{-i}^h	The sum of all SBs' net load at period h except for SB i
NL^h	The total net load of this system (denoted as system net load) at period h
$\mathrm{NL}_{\max}^h$	The maximum system net load in the specified period
LF	The load factor in the specified period
C_{sell}	The electricity cost of SBC
C_{overall}	The overall cost of SBC
C_i^h	The total cost of SB i at time period h
C_i	The total cost of SB i in the specified time horizon
E_i	The payoff of SB i
Pr	The electricity price offered by the SBCO to all the SBs
$P_{sbc}{}^h$	The overall profit of the SBCO at period h
$\mathrm{P}_{sbc}{}_i^h$	The profit obtained from SB i at period h
uc_i^h	The equivalent cost due to inconvenience caused by the load adjustment of SB i at period h
β_i	The convenience sensitivity coefficient of SB i

ing the similar general objective, i.e., minimizing the energy cost without affecting the overall comfort of users. BEMS with combined heating/cooling systems and power system optimizations is described in Refs. [11,12]. The multi-agent control system with heuristic intelligent optimization is developed in Refs. [13–15]. In Ref. [16], a system architecture is presented for load management in SBs, which is composed of three main modules for admission control, load balancing, and demand response management, respectively. An agent-based approach is proposed to optimize the inter-operation of the smart grid BEMS framework in Ref. [17], and numerical results from an integrated simulation showed that the operation of the building can be dynamically modified to support the voltage control of the local power grid, without jeopardizing the building's main function. In addition, energy forecasting models are essential for BEMS. Three general categories of building energy forecasting models have been reported in Ref. [18].

The aforementioned literature mainly focuses on the energy management of individual SBs. With the advancement of SB technologies in the upcoming years, the concept of Smart Building Cluster (SBC) is being naturally developed. The SBC consists of multiple neighboring SBs, which are electrically interconnected to the same medium-voltage distribution line or the same micro-grid. In the smart grid, the joint operation of SBs would be more advantageous than the independent operation of individual SBs due to the following considerations. Firstly, the load demand of SBC is far more than individual SB, thus the SBC can act as a large electricity consumer. Generally the larger consumer can have privilege to directly negotiate with the electricity generators, and is more likely to get favorable and flexible electricity prices according to the energy policy of some countries. Secondly, the SBs' surplus Renewable energy (RE) can be sold back to the power grid, or be shared with other SBs. In order to alleviate the effect of uncertainty of RES on the power grid, local consumption and regulation of RES energy on the distribution system or micro-grid level are preferable. Thus, the Smart Building Cluster Operator (SBCO) can act as an agent for sharing of RES power among adjacent SBs.

For the above reasons, effective energy management of SBC is highly needed to deal with the complexity of building operations and coordinate all SBs within the SBC. It could also help to achieve cost reduction and load characteristic optimization by taking advantages of DR and RES more effectively. However, little research has been devoted to efficient energy management of SBC or similar integrated building systems. This paper will focus on a multi-party energy management model for SBC, considering building-integrated PV systems and Automatic Demand Response (ADR). The main contributions of this study are listed in the following:

1) An energy management framework for operation of SBC is proposed, and the information exchange processes between SBCO and the participating SBs are introduced.
2) An optimization model for operating the SBC is proposed. The model is designed based on a non-cooperative game theory, where all the participating SBs are treated as players.
3) The process of solving Nash equilibrium strategy of the model is equivalent to tackling a multi-objective optimization problem, and corresponding algorithm and procedure based on an iterative method are proposed.

2. Energy management framework of SBC

2.1. System architecture and functions

The system architecture of the SBC with PV systems is shown in Fig. 1. Each SB is comprised of BEMS, PV source, load, intelligent electric meters, and so on. PV source is the first choice for an SB, which will purchase electricity through the SBCO when the PV source cannot satisfy the load demands. On the other hand, if the load demand of an SB is less than the production of the PV source, the redundant PV power output will be sold to other SBs or fed back to the utility grid at different prices. The SBCO is an agent for all the SBs, and it is also the EMS executor in the SBC. It is mandatory to ensure the interoperability among various components in Fig. 1. The SBCO is in charge of purchasing electricity from electricity generators in the utility grid or from the SBs with surplus RES power output, and then selling electricity to SBs within the SBC.