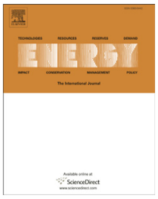
Energy 84 (2015) 759–773

Contents lists available at ScienceDirect

Energy

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



A collaborative operation decision model for distributed building clusters

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ARTICLE INFO

Article history:
Received 7 December 2014
Received in revised form
19 February 2015
Accepted 14 March 2015
Available online 10 April 2015

Keywords:
Smart buildings
Collaborative decision
Multi-objective optimization
Pareto optimality
Combined cooling heating and power system

ABSTRACT

In the context of smart grid, the building can freely connect with other buildings to form clusters which are termed as building clusters to share energy. However, less study is conducted to develop optimal operation strategy for building clusters and evaluate the performance of building clusters in terms of different measures under different operation modes. Therefore, this research proposes a collaborative decision model to study the energy exchange among building clusters where the buildings share a combined cooling, heating and power system, thermal storage, and battery, and each building aims to minimize its energy cost, carbon emission or primary energy consumption. A collaborative decision framework is proposed to obtain Pareto operation decisions for the building clusters. We compare the performance of the collaborative strategy with the non-cooperative strategy where no energy sharing among the buildings. It is demonstrated that the collaborative strategy can significantly reduce energy cost, carbon emission and primary energy consumption under both grid connected and disconnected operation modes. The collaborative strategy under dynamic pricing plan is more cost effective than the strategy under flat pricing plan, which indicates that the collaborative strategy can motive buildings to more efficiently utilize the shared energy under dynamic pricing plan.

1. Introduction

Among all the consumption units, buildings (approximately half commercial and half residential) consume over 70% of electricity [1]. To improve the energy efficiency of buildings, an initiative of smart building [2] is promoted. The potential advantages of smart building lie in the fact that it can take measures to improve the energy performance of energy devices and utilize novel sustainable technologies to produce electricity and thermal energy. Thus, extensive research in the past two decades focuses on developing optimal operation strategies for smart buildings with the application of on-site generation and energy storage [3].

In the building operation, the economic and environmental performance can be improved by introducing the energy storage, such as battery and thermal energy storage. Similar to the passive thermal storage system, the active thermal storage system can be operated as a buffer, which can smooth the dramatic variation of energy demand and decrease total energy costs. For example, Lee et al. [4] adopt particle swarm algorithm to obtain optimal operating strategies for the ice-storage air-conditioning systems to minimize life cycle cost. Liu et al. present the theoretical foundation [5] and practical evaluation [6] of reinforcement learning for optimal control of building active and passive thermal storage. Drees and Braun develop a rule based near-optimal control strategy for a thermal energy storage [7]. Mago et al. [8] demonstrate that the thermal energy storage can assist the CCHP (combined cooling, heating and power) system to achieve more cost savings for different types of commercial buildings. Bianchi et al. [9] show that integrating the CCHP system with an electric energy storage and a thermal energy storage in the residential building could significantly increase the profit for energy consumers.

The initial study of on-site energy generation for operating and controlling buildings focuses on the hybrid energy system with renewable energy. Manolakos et al. [10] propose a simulation optimization program to optimally operate and control a hybrid energy system including a battery, wind generator and photovoltaic module. A model-free reinforcement learning algorithm is developed [11] to adaptively control a grid-independent photovoltaic

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http://dx.doi.org/10.1016/j.energy.2015.03.042
0360-5442/

system with a collector, storage and load, which can effectively improve the energy performance in comparison to the conventional control strategy. The energy efficiency of a hybrid wind/photovoltaic/fuel cell generation system can be significantly improved using a fuzzy logic control and management system [12].

Among most of the attempts to increase the efficiency of on-site distributed generators through introducing renewable energy and new generation techniques, CCHP is broadly identified to be a promising technology capable of achieving more cost savings and reducing the greenhouse gas emission [13]. The development and prospect of CCHP technology is reviewed in Ref. [14]. It is demonstrated that the design of CCHP system with optimal prime mover capacity can significantly improve its efficiency [15]. The performance of CCHP system can be improved by integrating with other energy sources [16], and energy storage system [17]. Given the application of CCHP system in smart buildings, the performances of this integrated energy system largely depend on the operational strategies. For instance, a dynamic programming model is proposed by Facci et al. [18] to determine the optimal set-point for the CCHP, which is demonstrated that the optimal strategy can significantly reduce the total daily cost. Bischi et al. [19] utilize a mixed integer linear programming model for planning the short-term operation of CCHP system to minimize the total operating and maintenance costs. Considering uncertainties in weather conditions, energy demand and energy price, stochastic modeling is adopted to optimize the performances of the CCHP system. Li et al. [20] propose a stochastic programming model, which integrates Monte-Carlo method and mixed-integer nonlinear programming, to formulate the CCHP operation problem under uncertain energy demands.

Other than single criterion analysis of building energy systems, various criteria including operational cost, PEC (primary energy consumption), and CDE (carbon dioxide emission) are employed in the existing literature. For example, multiple criteria models, such as economic and environmental model [21], three criteria model based on operational cost, PEC and CDE [22], are proposed to evaluate the performance of CCHP system. To study the tradeoff among various criteria, the multi-objective approaches are employed to optimize the building energy system operation. Wu et al. [23] propose a multi-objective mixed integer nonlinear programming model to find the optimal operation strategies of a building CCHP system and further analyze the performance of the system under various load conditions. A MOO (multi-objective optimization) model is proposed in Ref. [24] to simultaneously optimize the CCHP system based on exergetic efficiency, total system levelized cost rate, and environmental cost rate. Taking the operational cost, PEC and CDE into account, Hu and Cho [13] exploit a probability constrained MOO model for an office building's CCHP system to guarantee the obtained optimal strategy is reliable to satisfy uncertain energy loads.

While promising, we notice that most literature related to the operation of buildings energy system focuses on developing optimal operation strategy in a single building, and attaches less attention to energy sharing and competition among multiple collaborative buildings which are termed as building clusters. To the best of our knowledge, the first attempt can be found in Ref. [3], where a bi-level operation decision framework for an integrated building clusters system is proposed. Furthermore, an augmented multi-objective particle swarm optimization algorithm is utilized for the decision framework, which is capable of deriving favorable results with better computational performance [25]. Although the proposed collaborative building clusters can significantly reduce energy cost, a quantitative model to evaluate the performance of collaborative building clusters in terms of different measures (e.g., cost, CDE) under different operation modes (e.g., grid connected/disconnected) is missing. The advantages of using CCHP, a promising energy system, in building clusters have not yet been quantitatively evaluated. Therefore, the purpose of this work is to develop a collaborative decision model to optimally operate the building clusters which share a CCHP system, battery and thermal energy storage, and comprehensively evaluate the performance of the building clusters in terms of cost saving, primary energy saving, and carbon emission reduction. In this research, the building clusters can freely share energy and exchange information, and each building has its objective to minimize energy cost, PEC or CDE. Please note that each building may have a conflict objective that cannot be optimized simultaneously, therefore we propose three multi-objective operation decision models to study the coordination among the building clusters in terms of cost saving, primary energy saving, and carbon emission reduction respectively. In order to examine the performance of the proposed collaborative strategy, we compare the simulation results of the proposed strategy to that of non-cooperative operation strategy under fixed and dynamic pricing mechanisms. In addition, we conduct extensive analysis to investigate the performance of the building clusters under different operation modes (grid connected/disconnected) using different measures.

This paper is organized as follows. Section 2 introduces the structure of the building clusters. The mathematical model for the building clusters is discussed in Section 3. The collaborative decision framework for the building clusters operation is established in Section 4. Section 5 presents numerical experiments under different scenarios to examine the performance of the proposed operation strategy, and conclusions are drawn in Section 6.

2. Building clusters with CCHP system architecture

Fig. 1 shows the structure of an integrated building clusters system which consists of a CCHP system, thermal energy storage, battery, and two buildings. The CCHP, thermal storage and battery are shared by these two buildings. The PGU (power generation unit) adopts a gas turbine as its prime mover to generate electricity and a recovery system to produce heating energy. An absorption chiller and a heating exchanger are used as the cooling and heating components in the system.

The solid line represents electric energy flow and the dashed line represents thermal energy flow. The electric load of each building is supplied by CCHP, battery and power grid. The power grid will power the buildings if the electricity generated by both CCHP and battery cannot satisfy the electric load, and otherwise, the surplus electric energy produced by PGU will be sold back to the power grid. The thermal energy load of each building is satisfied by CCHP and thermal storage system. The auxiliary boiler converts fuel into heat to compensate the shortage of cooling and heating load. The thermal storage system will be charged by both the PGU and auxiliary boiler.

As demonstrated in Fig. 1, the two buildings should cooperate with each other to optimally operate the CCHP, thermal storage and battery to converge to a win–win (Pareto) decision which aims to minimize each building's energy cost, PEC or CDE. To assist the collaborative operation among multiple buildings, a multi-objective operation decision model will be proposed to derive Pareto operation decisions in this research. The detailed mathematical model is described in the next section.

3. Mathematic model for collaborative building clusters operation

In this section, we develop a multi-objective mixed integer programming model to study the energy sharing and collaboration