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Impacts of renewable energy system design inputs on the performance robustness of net zero energy buildings

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ABSTRACT

Due to the intermittent and uncontrollable nature of renewable energy resources, the performance of nZEB (net zero energy buildings) may suffer a great degree of uncertainties. In this study, a GA (genetic algorithm) optimization approach is employed to search optimal sizes of four design options for a net zero energy building. Then, sensitivity analysis is conducted on an optimized system (photovoltaic/wind turbine/bio-diesel generator) to investigate the impacts of the design input variations on the building performance (i.e. operation cost, CO_2 emission, impact on grid). The results show that, with 20% variations in the four variables, the maximum change of the combined objective is 26.2%. In addition, wind velocity is the key factor concerning mismatch ratio, the cost and CDE (CO_2 emissions), while the building loads should be considered with high priority concerning the comprehensive performance (combined objective) of the building. The performance of the energy system, integrating photovoltaic and bio-diesel generator, is not the best. But, compared with the other three design options, the variations of operation variables have least effects on its performance (i.e. most robust performance). The results also provide the quantitative assessment on the impact of active energy generation systems on enhancing the performance robustness of net zero energy buildings.

1. Introduction

Uncertainty and variability are inherent features of any process or system especially in system design and operations [1]. In order to overcome the uncertainty and variation of the world, one needs to take appropriate management action to respond to the changing environment. Sensitivity analysis is a valuable tool for decision-makers to explore the impacts of the changes in input variables on model outputs. In recent years, the use of sensitivity techniques has been popularized for applications in different fields, such as environmental modeling and assessment applications [2–4], investment projects in business [5,6], engineering projects [7–11] and other applications [12–14]. Buildings consume approximately 40% of the total energy utilization [15] and this percentage for the building sector in Hong Kong is even much higher (over 90% of electricity [16]). Sensitivity analysis has been used to identify the key factors affecting building energy/thermal performance from both observational study and energy simulation models. The objectives include the exploration of the characteristics of building energy/thermal performance in different applications, such as building retrofit [11,17], building stock [18,19] and impacts of climate change on buildings [20,21].

Many efforts have been made in the areas of sensitivity analysis on design parameters in traditional building energy systems [22–26]. Most of these efforts focused on identifying the key parameters that affect peak loads, energy consumption/cost and thermal comfort. Lam and Hui [22] conducted a sensitivity study on the building system design parameters of an office building in Hong Kong. The most significant design parameters in that study were identified and analyzed in terms of peak design loads, building load profile and building annual energy consumption. Similarly, Heiselberg et al. [23] applied sensitivity analysis to identify the important design parameters affecting building performance in order to reduce the primary energy consumption. Wang [24] studied uncertainties in energy consumption due to building operational practices and the actual weather, based on the simulation of a medium-size office building. The results show that poor operations may cause an increase of 49–79% in energy use across the selected cities, while good practice reduces energy use by 15–29%. The energy use may vary from −4% to 6% due to the year-

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to-year weather fluctuation. In a study on the building energy consumption data collected in a city in China, Lu et al. [25] conducted a quantitative uncertainty and sensitivity analysis. The main sources of uncertainties affecting the total energy consumption were identified and effective means to reduce the uncertainty of the provision of energy were proposed for decision-makers. Tian [26] pointed out that sensitivity analysis plays an important role in building energy analysis. He reviewed the sensitivity analysis methods and the implementation of sensitivity analysis in building performance evaluation.

Unlike traditional buildings, the energy generation systems installed in low/zero energy buildings mainly depend on the renewable energy resources of intermittent and uncontrollable nature (e.g. solar radiation, wind). The application of energy storage systems in buildings could assist to enhance the load match of the building through the reduction of the dependence of the building on the uncertainty of renewable systems generation [27–30]. Guarino et al. [27] analyzed the performance of PCMs (phase chang materials)PCMs in residential housing for different climates through an experimental study. In another study [28], the minimum size of the energy storage was identified to improve energy load match between energy generation and energy consumption. Lu et al. [29] adopted the MPC method based on mixed-integer nonlinear programming to optimize the operation of integrated energy systems in low energy buildings under day-ahead electricity price. A few studies have been conducted on the uncertainty/sensitivity analysis in the design of renewable energy systems in buildings. Maheri [31] studied the uncertainties in renewable resources, demand load and power modeling in the optimal design of a standalone wind-PV-diesel hybrid system. Ren et al. [32] studied the optimal design of a grid-connected PV (photovoltaic) system considering the uncertainties in the efficiency and cost of PV systems. The sensitivity of levelized cost and simple payback period to various economic and technical circumstances were also analyzed. Zhou [33] proposed a two-stage stochastic programming model for the optimal design of distributed energy systems. The impacts of demand and supply uncertainties on the design optimization were investigated and compared with the deterministic optimal design. The results indicate that the negative impacts of energy demand and supply uncertainties can be reduced by introducing grid connection and energy storage. Ashouri [34] investigated the design of building energy systems taking into account the uncertainties of boundary conditions such as weather conditions and user demands. The results of sensitivity analysis indicate that, when the robustness of the energy systems designed was concerned, the equipment sizes might vary up to 100% compared with the system designed using the traditional method. Similar studies could also be found in other studies [35–40].

Over the last decades, studies on nZEB (net zero energy buildings) can be categorized into several subject areas, including different definitions and evaluation methods [41,42], system design and configurations [43–45], case study/demonstration projects [46–48] and management optimization of energy systems [29,30]. Very few studies can be found concerning the sensitivity analysis on system design parameters of nZEB as stated by Sun [44]. He, therefore, proposed a dynamic simulation platform to study the impacts of each building parameters (i.e. wall thickness, window to wall ratio, infiltration rate etc.) on the sizes of main energy systems in net zero energy buildings. Bucking et al. [49] proposed a methodology to identify the influential variations on the building performance metric, which helps to understand possible discrepancies between predicted and realized building performance. However, the sensitivity of the energy system performance of net zero energy buildings to the discrepancies between the real and design operation conditions (e.g. weather condition and demand load) are not yet clear based on the above studies.

This paper therefore presents a sensitivity analysis on the impacts of the major inputs for renewable energy system design and the study on the performance robustness of different design options for a net zero energy building. This paper is structured as follows. Section 2 presents an outline and the framework of sensitivity analysis method. In Section 3, the building studied and the performance measures used in design optimization are introduced. Section 4 presents the results of the sensitivity analysis on a system combining PV (photovoltaic), WT (wind turbine) and BDG (bio-diesel generator) and the comparison on the performance robustness of different design options. Conclusions are given in Section 5.

2. Outline of methodology

Fig. 1 shows the approach and steps of the sensitivity analysis to evaluate the performance of buildings with different energy system design options. At the first step (Step I), an optimization software tool based on GA (genetic algorithm) is implemented to obtain the optimal sizes of renewable energy systems and the corresponding building performance. The genetic algorithm is a method for solving both constrained and unconstrained optimization problems that is based on natural selection, the process that drives biological evolution. The genetic algorithm repeatedly modifies a population of individual solutions. At each trial, the genetic algorithm selects individuals at random from the current population to be parents and uses them to produce the children for the next generation. Over successive generations, the population "evolves" toward an optimal solution [50]. GA is now one of the most preferable and widespread searching algorithms for optimization problems. It is easy to be transferred in existing simulations and models. The values of weather data and occupancy/equipment schedules, the parameters of energy systems and renewable energy systems are set as the inputs and parameters for building model and the energy system models. TRNSYS (a complete and extensible software environment for the transient simulation of systems) [51] building model is used to calculate the cooling load. The models of energy and renewable energy systems are developed and implemented in Matlab (2006). The size ranges of renewable energy systems are set as the constraints for the GA optimizer (included in Matlab 2006). The objective function, combining the TC (total annualized cost), CDE (CO_2 emissions) and the GII (grid interaction index) using weighting factors shown in Eq. (1), is evaluated and minimized by the GA optimizer based on trial values of renewable energy system sizes.

At the second step (Step II), the comprehensive performance of the building, when the input variables vary over certain arranges, is computed using the objective function and the same building energy and renewable energy system models. Four most important input variables representing the working condition of buildings are selected and each of them is assigned with a variation range. In this study, the input variables concerned include wind velocity, solar radiation, building cooling load and building electric load. The solar radiation and wind velocity in the typical year (1987) are added with variations of a given range (20%). The building cooling load refers to the total cooling needed from the chiller plant. It is calculated using the TRNSYS building model as explained above. The building electric load refers to the total building electric load of all electricity appliances in the building except the air-conditioning system. The typical cooling load and building electric load are also assigned with variations in a given range (20%).

At the third step (Step III), based on the optimal system size determined at Step I and the input variables associated with their variation distributions determined at Step II, the one-way