Energy 94 (2016) 654–665

Contents lists available at ScienceDirect

Energy

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

A multi-criterion renewable energy system design optimization for net zero energy buildings under uncertainties

Sheng Zhang [a], Pei Huang [b], Yongjun Sun [a, *]

[a] Division of Building Science and Technology, City University of Hong Kong, Hong Kong
[b] Department of Architecture and Civil Engineering, City University of Hong Kong, Hong Kong

A R T I C L E I N F O

Article history:
Received 23 September 2015
Received in revised form
27 October 2015
Accepted 10 November 2015
Available online 17 December 2015

Keywords:
Net zero energy building
Renewable system design
Uncertainties
Annual energy balance
Grid stress
Initial investment

A B S T R A C T

Net zero energy buildings (NZEBs) are promising to mitigate the increasing energy and environmental problems. For NZEBs, annual energy balance between renewable energy generation and building energy consumption is an essential and fundamental requirement. Conventional RES (renewable energy system) design methods for NZEBs have not systematically considered uncertainties associated with building energy generation and consumption. As a result, either the annual energy balance cannot be achieved or the initial investment of RES is unnecessarily large. Meanwhile, the uncertainties also have significant impacts on NZEB power mismatch which can cause severe grid stress. In order to overcome the above challenges, this study proposes a multi-criterion RES design optimization method for NZEBs under uncertainties. Under the uncertainties, Monte Carlo simulations have been employed to estimate the annual energy balance and the grid stress caused by power mismatch. Three criteria, namely the annual energy balance reliability, the grid stress and the initial investment, are used to evaluate the overall RES design performance based on user-defined weighted factors. A case study has demonstrated the effectiveness of the proposed method in optimizing the size of RES under uncertainties.

1. Introduction

As reported by International Energy Agency, the building sector accounts for 40% of the primary energy use and 24% of the greenhouse gas emissions worldwide [1]. Prompting the energy management in the building sector has the greatest potential to reduce energy demand and greenhouse gas emission [2]. In this context, net zero energy buildings (NZEBs) are wildly accepted as a promising solution to mitigate the energy and environmental problems [3]. NZEBs are innovative building typology that can achieve zero energy consumption annually [4]. It has been successfully achieved in mangy demonstrative projects [5], and adopted as compulsory target for the building sector in many countries/regions such as the USA and Europe [6].

NZEBs fully rely on renewable energy system (RES) to realize annual energy balance [7]. Annual energy balance refers to that the energy generated by RES annually can cover the total energy consumed by buildings in that year [8]. Annual energy balance is an essential and fundamental requirement for NZEBs, though the definition of NZEBs may vary due to the discrepancies in culture, economy, policy and geographical location [4]. For example, a site NZEB requires annual energy balance accounted at the building side [9]. In contrast, a source NZEB claims annual energy balance achieved at the source side, where the energy loss in the transmission process is also considered in the calculation of annual energy consumption [8]. A NZEB with net-zero emission is designed to achieve annual energy balance by generating sufficient energy from RES to offset emissions from other conventional energy sources which it uses [10].

Unfortunately, due to the uncertainties associated with the renewable system energy generation and building energy consumption, NZEBs are easy to fail in achieving such annual energy balance. The uncertainties can be classified into three categories: physical parameters, design parameters and scenario parameters [11]. Physical parameters denote parameters related to physical properties of materials. Design parameters denote parameters related to pre-set working condition during planning process. And scenario parameters denote parameters related to real-time operation. These uncertainties have significant impacts on renewable system energy generation and building energy consumption. For

* Corresponding author. Tel.: +852 34422672; fax: +852 34429716.
E-mail address: yongjsun@cityu.edu.hk (Y. Sun).

http://dx.doi.org/10.1016/j.energy.2015.11.044
0360-5442/

example, uncertainties in the scenario parameters (e.g. solar radiation) make the renewable system energy generation intermittent and unstable [12]. Uncertainties in the physical parameters, design parameters and scenarios parameters can cause the instant building energy easily to deviate from the expected value [13,14]. Due to these uncertainty impacts, the annual energy balance in NZEBs is stochastic and hard to be achieved in practice.

In order to ensure the annual energy balance, conventional RES design methods commonly select over-sized RES that leads to unnecessarily large initial investment [15]. The conventional RES design methods determine RES size using two approaches: the worst scenario and adding safety factors. In the former approach, the input parameters for annual energy consumption were selected from the worst scenario to make it reach the maximum value, and then the maximized annual energy consumption was used to size the RES. The worst scenario approach easily results in overestimated annual energy consumption [16]. In the latter approach, the annual energy consumption was calculated at a typical scenario, and then a safety factor (larger than 1) was defined by the users to size the RES [17]. Thus, RES designed from the approach heavily depended on the designers' experience and it was easy to be over-sized.

To investigate the uncertainty impacts on NZEB system (i.e. HVAC and RES) design, a multi-criterion design optimization method has been proposed in Ref. [15]. In that method, the uncertain peak cooling load was used to size the HVAC system, and then the annual energy consumption of the HVAC system was used to size the RES. Finally, the optimal NZEB system sizes were selected under the framework of multi-criterion decision making considering three criteria: the indoor thermal comfort, the grid stress and the initial investment. This design method took account of the uncertainty impacts and made trade-off between different criteria. However, the renewable system energy generation uncertainties and the building energy consumption uncertainties have not been considered during the RES size selection at a given HVAC size. Meanwhile, the annual energy balance, the essential requirement for NZEBs, has not been considered in the design process. As a result, the RES designed from that method may not be the optimal one: either the annual energy balance cannot be achieved or the initial investment is unnecessarily large. To overcome such challenges, RES design for NZEBs should consider both the annual energy balance reliability and the initial investment under uncertainties related to the energy generation and consumption.

RES design for NZEBs also needs to consider the grid stress caused by power mismatch [18]. The power mismatch refers to the mismatch between renewable system energy generation and building energy consumption in a short term, such as one hour. The power mismatch is an inherent characteristic of NZEBs and it fluctuates due to the uncertainties of energy generation and consumption. Fluctuating power mismatch leads to fluctuating energy import from/export to the grid, and eventually the stress on grid power balance and supply quality is caused [19]. Apart from the energy-related criteria (i.e. annual energy balance and power mismatch) and economic factor (i.e. initial investment), customer preference is also a decisive factor in sizing the RES [20]. Different NZEB customers may have different preferences towards different criteria which can influence the design results significantly [21]. For example, some customers prefer the annual energy balance to the initial investment, and thus they are likely to take a large sized RES. However, other customers may behave in the opposite way.

In order to properly size RES for NZEBs under uncertainties related to the energy generation and consumption, this study proposes a multi-criterion RES design optimization method for NZEBs. Three criteria, namely annual energy balance reliability, grid stress and initial investment, will be considered. Customer preferences are quantified by assigning the weighted factors to the criteria. Via three stages, the proposed method determines RES size for NZEBs with a given HVAC system configuration. At the first stage, RES size search range is derived based on conventional RES design result. At the second stage, under uncertainties, Monte Carlo simulation is conducted to estimate power mismatch and annual energy balance of each RES size within the search range from the first stage. At the third stage, the optimal RES size is determined based on overall performance evaluation. To demonstrate the effectiveness of the proposed method, case studies will be conducted and the results will be compared with a conventional RES design.

2. Methodology

2.1. Overview of the proposed RES design optimization for NZEBs

Fig. 1 shows the main idea of the proposed RES design optimization method for NZEBs. The proposed method contains three stages: RES size search range identification, estimation of power mismatch & annual energy balance, and multi-criterion decision making. The first stage is to identify RES size search range for NZEBs with a given energy consuming system configuration. The largest RES in this search range is sized to meet the maximum annual energy demand (D_{max}) estimated by a conventional RES design method (e.g. the worst scenario method). And the smallest RES in this search range is sized to meet the minimum annual energy demand (D_{min}). The minimum annual energy demand, defined by the users, is a certain percentage (e.g. 50%) of the maximum annual energy demand. In the study, a set of RES sizes are selected to meet the annual energy demand options that are between the maximum and the minimum values (i.e. $D_{min} \le D_1, D_2, \ldots, D_q \le D_{max}$). Noted that the annual energy demand options are not the actual building annual energy demand but the user selected demand values for RES sizing. The RES investigated in this study consists of PV (photovoltaic panel) and WT (wind turbine).

The second stage aims to estimate power mismatch & annual energy balance under uncertainties. The power mismatch and the annual energy balance are obtained through investigations of RES hourly-average power generation and HVAC hourly-average power consumption. The RES hourly-average power generation suffers from scenario parameters while the HVAC hourly-average power consumption suffers from uncertainties of physical parameters, design parameters and scenario parameters. As a common method to deal with uncertainties [22], Monte Carlo is employed in this study to investigate RES the hourly-average power generation and the HVAC hourly-average power consumption under uncertainties. It should be noted that power production from RES may have significant variation within an even shorter period (e.g. one minute), due to the varying weather condition such as solar radiation and wind velocity. In this study the hourly average power generated from PV and WT was calculated using the hourly average weather data. The main reasons are as follows: *i)* Although recently NZEB studies have moved towards higher-resolution data, from monthly down to hourly and sub-hourly resolutions [23,24], the most widely used time resolution in building simulation and design is still hourly, and the use of higher-resolution data is still uncommon [25]; *ii)* The computational cost will be 60 times higher if the power generation is estimated from every hour to every minute; *iii)* In current popular simulation software such as TRNSYS and EnergyPlus, only hourly weather data are available [26,27].

The third stage targets at optimizing RES size according to the overall performance evaluation results. The overall performance evaluation is in fact a multi-criterion decision making process. The multiple criteria considered in the study include annual energy