Energy and Buildings 89 (2015) 61–75

Contents lists available at ScienceDirect

Energy and Buildings

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

Renewable energy system optimization of low/zero energy buildings using single-objective and multi-objective optimization methods

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ARTICLE INFO

Article history:
Received 10 November 2014
Received in revised form
10 December 2014
Accepted 16 December 2014
Available online 24 December 2014

Keywords:
Low energy building
Zero energy building
Renewable energy system
Genetic Algorithm
NSGA-II
Single objective optimization
Multi-objectives optimization

ABSTRACT

Low energy buildings and zero energy buildings have attracted increasing attention in both academic and professional fields. The performances of these buildings are largely affected by the design of the renewable energy systems. This paper presents a comparison study on two design optimization methods for renewable energy systems in these buildings, including a single objective optimization using Genetic Algorithm and a multi-objectives optimization using Non-dominated Sorting Genetic Algorithm (NSGA-II). Building energy system models and renewable energy system models are developed and adopted, allowing the consideration of the interaction between building energy systems and renewable energy systems in optimization. Two case studies are conducted to evaluate the capability and effectiveness of proposed optimization methods, based on the Hong Kong Zero Carbon Building. The performances of the buildings with the renewable energy systems optimized by both methods are much better than that of the benchmark building in most scenarios. The single objective optimization can provide the "best" solution directly for a given objective while the multi-objective optimization provides rich information for designers to make better compromised decisions.

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1. Introduction

Energy conservation, carbon reduction and pollutant emissions reduction are three of the biggest challenges to governments, professionals and society today. Buildings consume over 40% of end-use energy worldwide [1] and this percentage for building sector is even higher (over 60% of primary energy and over 90% of electricity [2]) in Hong Kong. In order to address these issues, the U.S. has set a zero energy target for 50% of commercial buildings by 2040 and for all commercial buildings by 2050 [3]. In Europe, the Directive on Energy Performance of Buildings establishes a "nearly net zero energy buildings" as the target for all new buildings from 2020 [4]. Similarly, the Hong Kong government has set a target for carbon reductions: carbon intensity should be reduced by 50–60% by 2020 compared with 2005 baseline [5]. Over the last decades, increasing demos of zero energy buildings are developed all over the world [6–9]. Zero energy building (ZEB) integrated with micro-grid is becoming a future trend for constructing new buildings and renovating existing buildings.

Over the last decades, researches on ZEB have been mainly concerned with different definitions and evaluation methods for ZEB [10,11], building design and system configuration [12,13], demonstration of buildings integrated with renewable energies [14,15], and design/management optimization [16–18]. Increasing attention has been paid on how to design low/zero energy buildings in a cost/energy-saving and environment-friendly way [16,18]. Thalfeldt et al. [16] presented an investigation on cost optimal solutions for nearly zero energy buildings regarding building facade solutions, including window properties, external wall insulation, shading and the ratio of window-to-wall. Kurnitski et al. [18] developed a seven-step procedure to conduct cost optimal and NZEB energy performance levels calculations. Based on simulation, four construction concepts were investigated involving building envelops from normally used construction to highly insulated building envelop. These optimization studies focused mainly on optimal design of zero energy buildings concerning on the building thermal parameters. In addition, minimizing the system cost is usually chosen as the function to attain the optimal design strategies. However, the environmental issues, such as CO_2 emissions and the interaction of ZEB with electricity grid have not been taken into account in most studies. Therefore, multi-objective optimization should be a better approach to evaluate the performance of ZEB comprehensively.

Effective optimization methods are essentially needed for optimal design/control of buildings and the energy systems. Sun et al. [19] proposed a multiplexed optimization scheme and compared it

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http://dx.doi.org/10.1016/j.enbuild.2014.12.032
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Nomenclature

A_{des}	total area of PV (m^2)
A_{WT}	area of blade (m^2)
$c_{p,w}$	coefficient of the wind turbine performance
CDE_{ele}	carbon dioxide emissions of grid electricity (kg)
CDE_{bio}	carbon dioxide emissions of bio-diesel combustion (kg)
CDE_{BB}	carbon dioxide emissions of "benchmark building" (kg)
CDE_n	the normalized carbon dioxide emissions
cde_{ele}	emission factor of grid electricity (kg/kWh)
cde_{bio}	emission factor of bio-diesel combustion (kg/l)
$cost_{operation}$	annual operation cost including oil cost and electricity bill (USD)
$cost_{resi}$	annual renewable energy system investment cost (USD)
COP_{ec}	coefficient of performance of electric chiller
COP_{ac}	coefficient of performance of absorption chiller
COP_N	normal capacity of chiller
F_{bio}	fuel consumption of the bio-diesel generator (l)
$f_{grid,i,T,BB}$	grid interaction index of "benchmark building"
$f_{grid,i,T,n}$	the normalized grid interaction index
GII	grid interaction index
I_{irra}	hourly irradiance (kWh/m^2)
m_w	water flow rate (m^3/s)
Δp_{cwp}	pressure drop of cooling water pumps (kPa)
Δp_{fan}	pressure head of the fan (kPa)
Δp_{sen}	pressure drop after the pressure sensor point (kPa)
Δp_{others}	pressure drop in other parts of the air system (kPa)
P_f	packing factor
PLR	partial cooing load ratio
Q_c	building cooling demand (kW)
Q_{ac}	cooling provided by the absorption chiller (kW)
Q_{ec}	cooling provided by electric chillers (kW)
Q_r	heating demand by the absorption chiller (kW)
$T_{eva,out}$	outlet water temperature of the evaporator (°C)
$T_{con,in}$	inlet water temperature of condenser (°C)
$T_{wb,in}$	wet-bulb temperature of the cooling tower inlet air (°C)
TC	annual total cost (USD)
TC_{BB}	the total cost of "benchmark building" (USD)
TC_n	the normalized total cost
v_{wind}	wind velocity (m/s)
w_1, w_2, w_3	weighting factors
W_{ex}	exported electricity (kW)
W_{im}	imported electricity (kW)
W_{BDG}	power generation of generator (kW)
$W_{BDG,Rated}$	rated power generation of generator (kW)
W_{PV}	power generation of photovoltaic (kW)
W_{WT}	power generation of wind turbine (kW)
W_{ec}	power consumption of electric chillers (kW)
W_{pump}	power consumption of pumps (kW)
W_{ct}	power consumption of cooling tower fans (kW)
W_{fan}	power consumption AHU fans (kW)
W_{supply}	electrical supply (kW)
W_{demand}	electrical demand (kW)
η_{cwp}	pump efficiency
η_{fan}	fan efficiency
η_{BDG}	BDG efficiency
η_{hrs}	heat recovery system efficiency
η_m	PV module efficiency
ρ_a	air density (kg/m^3)
η_{WT}	combined efficiency of the generator and wind turbine
η_{PC}	power conditioning efficiency
υ_a	air flow rate (m^3/s)

with the genetic algorithm as regards computational load, energy performance and system stability. Case studies demonstrate the effectiveness and efficiency of the proposed optimization scheme. Ma and Wang [20] presented the test and evaluation of energy saving potentials of complex building central chilling systems on a simulated virtual system and GA was applied to search for the globally optimal control settings. Based on frequency domain regression using genetic algorithm (GA), Xu and Wang [21] presented a methodology for parameter optimization of 3R2C thermal network model of building envelops. The GA method involved in this study provides an efficient solution to the non-linear parameter regression and parameter optimization problem. As stated by Evins [22], over 50% of the works on building optimization were concerned with single objective problems, around 40% of works addressed multi-objective problems, while a few works applied a weighted-sum approach to transform multiple objectives into a single objective problem. Wang et al. [23] used structured genetic algorithms to address the economical and the environmental problem by the weighted-sum technique. The weighted-sum approach is a simple method to convert multi-objectives into one objective but the disadvantage is that only one set of optimal values can be obtained for each weighting set. Wang et al. [24] further employed a multi-objective genetic algorithm to examine the trade-off between economical and the environmental performance for green building design. The advantages of applying multi-objective approach are compared with the weighted-sum approach. Palonen et al. [25] developed a GA-based method to solve simulation-based optimization problems of optimal design of building envelopes and HVAC systems. The results of single and multi-objective optimizations were compared, showing the advantage of multi-objective approach on generating a diverse set of pareto-front value and capturing extreme solutions to all objective functions. Evolutionary algorithms are regarded as a common meta-heuristic optimization algorithm and widely used for optimizations in different fields. GA (Genetic Algorithm), as one type of evolutionary algorithms, is widely applied to solve objective optimization problems. The most common optimization method implemented for multi-objective problems is non-dominated sorting Genetic Algorithm-II (NSGA-II) [26].

Due to the integration of multiple energy generation systems in zero/low energy buildings, it is a quite complex task to analyze the optimal design and study the economic viability of the energy systems. Several software tools are available for the design of hybrid energy systems for power generation in urban, rural and remote areas (including in low/zero energy buildings). In their study, Sinha and Chandel [27] have compared 19 software tools including Hybrid Optimization Model for Electric Renewables (HOMER), HYBRID 2, Hybrid Optimization by Genetic Algorithms (HOGA) RETScreen, TRNSYS, etc. and their main features. HOMER is public domain program developed by National Renewable Energy Laboratory (NREL) [28]. It has been used extensively in previous energy system optimization [29–35]. Iqbal [30] studied the optimal design of hybrid alternative energy power systems (photovoltaic panel (PV), wind system and micro/small hydro-power plant) for zero energy buildings using HOMER. HOMER adopts a single objective optimization approach and sorts a list of configurations by comparing the net present cost of each system design options. Ma et al. [31] presented a techno-economic feasibility study on a standalone

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