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Uncertainty-based life-cycle analysis of near-zero energy buildings for performance improvements

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HIGHLIGHTS

- Develop a LCPA method considering uncertainties and degradation.
- Analyze how degradation affects nZEB thermal comfort, energy balance, grid independence.
- Prove an nZEB might not fulfil its definition at all after some years due to degradation.
- Develop a two-stage method to improve the nZEB life-cycle performance.

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ABSTRACT

Near-zero energy buildings (nZEBs) are considered as an effective solution to mitigating CO_2 emissions and reducing the energy usage in the building sector. A proper sizing of the nZEB systems (e.g. HVAC systems, energy supply systems, energy storage systems, etc.) is essential for achieving the desired annual energy balance, thermal comfort, and grid independence. Two significant factors affecting the sizing of nZEB systems are the uncertainties confronted by the building usage condition and weather condition, and the degradation effects in nZEB system components. The former factor has been studied by many researchers; however, the impact of degradation is still neglected in most studies. Degradation is prevalent in energy components of nZEB and inevitably leads to the deterioration of nZEB life-cycle performance. As a result, neglecting the degradation effects may lead to a system design which can only achieve the desired performance at the beginning several years. This paper, therefore, proposes a life-cycle performance analysis (LCPA) method for investigating the impact of degradation on the longitudinal performance of the nZEBs. The method not only integrates the uncertainties in predicting building thermal load and weather condition, but also considers the degradation in the nZEB systems. Based on the proposed LCPA method, a two-stage method is proposed to improve the sizing of the nZEB systems. The study can improve the designers' understanding of the components' degradation impacts and the proposed method is effective in the life-cycle performance analysis and improvements of nZEBs. It is the first time that the impacts of degradation and uncertainties on nZEB LCP are analysed. Case studies show that an nZEB might not fulfil its definition at all after some years due to component degradation, while the proposed two-stage design method can effectively alleviate this problem.

1. Introduction

As reported by the many studies, buildings consume about 40% energy worldwide [1], and this percentage even increases to more than 60% in Hong Kong [2]. Near-zero energy buildings (nZEBs) are considered as an effective solution for mitigating CO_2 emissions and reducing the energy usage in the building sector. Until now, a lot of efforts have been made on establishing regulations on nZEB for promoting its application. For instance, the European Directive on Energy Performance of Buildings introduces requirements that all the new buildings should be 'nearly net zero energy buildings' after 2020 [3,4]. The U.S. government sets a target that 50% of commercial buildings achieve zero-energy by 2040, and all commercial buildings achieve zero-energy by 2050 [5]. The International Energy Agency (IEA) Solar Heating and Cooling (SHC) program sets up the task 40 'Towards net zero energy solar buildings' to develop a harmonized international definition framework including tools, innovative solutions and industry guidelines [6].

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Nomenclature

Abbreviations

DoD	depth of discharge (dimensionless)
EMS	energy management system
ES	energy storage
LCA	life-cycle analysis
LCC	life-cycle cost
LCP	life-cycle performance
LCPA	life-cycle performance analysis
PV	PV panel
RES	renewable energy system
WT	wind turbine

Symbols

a_t	discount rate
A_R	rotor area of a wind turbine
AC_t	operational cost (HKD)
C_P	power efficiency of a wind turbine
CAP_{AC}	air-conditioning system capacity (kW)
CAP_{ES}	energy storage system capacity (kW h)
CAP_{PV}	PV surface area (m^2)
CAP_{WT}	capacity of wind turbine (kW)
CL	cooling load (W)
CL_{sup}	supply cooling capacity (W)
D_a	average degradation rate
D_{CL}	cumulative degradation rate of battery
E_{dem}	annual electricity demand (kW h)
E_{sup}	annual power production (kW h)
E_{store}	energy stored in energy storage system (kW h)
I_{AM}	combined incidence angle modifier for the PV cover material
I_T	total amount of solar radiation incident on the PV collect surface (W/m^2)
IC	initial cost (HKD)
P_{demand}	power demand from nZEB (W)
P_{PV}	power generated by a PV panel (W)
P_{WT}	power generated by a wind turbine (W)
Pow_{charge}	power charge of the energy storage system (W)
$Pow_{mismatch}$	power mismatch of the nZEB (W)
Q_0	amount when newly installed (it can be chiller capacity, pump efficiency, etc.)
Q_t	amount in the t^{th} year (it can be chiller capacity, pump efficiency, etc.)
r	interest rate
R_k	ranges of depth of discharge
t	year of operation
T_{room}	indoor air temperature (°C)
$T_{setpoint,cooling}$	indoor temperature set-point in cooling condition (°C)
$T_{setpoint,heating}$	indoor temperature set-point in cooling condition (°C)
$u_{ele,exp}$	unit price of exported electricity (HKD/kW h)
$u_{ele,imp}$	unit price of imported electricity (HKD/kW h)
u_{ac}	unit price of air-conditioning system (HKD/kW)
u_{es}	unit price of energy storage system (HKD/(kW h))
u_{pv}	unit price of PV panels (HKD/m^2)
u_{wt}	unit price of wind turbine (HKD/kW)
U_0	wind velocity (m/s)
$X(i)$	data points in the DoD file

Greek symbols

η	efficiency of the PV array
κ	transmittance-absorptance product of the PV cover
τ_j	value of cooling temperature set-point unmet hour in the *j*th hour (h)
ρ_{air}	air density (kg/m^3)
$\Psi_{balance}$	energy balance indicator (dimensionless)
$\Psi_{comfort}$	cooling temperature set-point unmet hour indicator (h)
Ψ_{grid}	grid independence indicator (dimensionless)
Γ	time duration

Proper sizing of nZEB systems is essential for ensuring that the nZEBs can perform as expected in terms of annual energy balance, thermal comfort, and grid independence [7–9]. A nZEB typically contains several types of systems, including energy consuming systems (e.g. HVAC systems, lighting systems, etc.), renewable energy systems (RES) (e.g. PV panels, wind turbine, etc.), energy storage systems, and thermal storage systems [10]. The sizing of these nZEB systems is interconnected: the building peak cooling/heating load is the basis for sizing the HVAC system; the energy demand from energy consuming systems is the basis for sizing the RES systems; the energy demand and energy supply are the basis for sizing the energy storage system. Two significant factors affecting the sizing of nZEB systems are the uncertainties embodied in the building usage condition and weather condition, and the degradation effects in components of systems [11–15]. The former factor may easily lead to oversizing of nZEB components due to inaccurate evaluation of the building energy demand [4,7–9]. For instance, oversizing of HVAC systems is common, and some systems are oversized by as much as 100% [11]. The latter factor may lead to a design that cannot perform as expected during the whole service life [16].

Uncertainties are defined as the information gap between what the decision makers' present state of information and certainty [17,18]. For nZEB system design, uncertainties exist in the physical properties (e.g. thermal conductivity, density) of building envelope, in the internal heat gain (e.g. occupant and electrical facility density), in the weather condition, etc. [7,9,19]. In recent years, the importance of uncertainties has been recognized by researchers, and many uncertainty-based design methods of nZEB systems have been developed [4,7–9,20,21]. For instance, Sun et al. [8] and Zhang et al. [9] proposed a multiple-criteria design method for nZEB system under uncertainties, which selects the optimal design in the framework of multiple criteria decision making. Three performance indices, namely initial cost, thermal comfort, and power mismatch, were considered in that method. Lu et al. proposed a single-objective and multi-objective optimization (Pareto optimization) approach of renewable energy systems of low/zero energy buildings and compared the performance of these two methods in system design [4]. Notably, Yu et al. proposed a generic-algorithm-based system sizing method considering multiple criteria performance constrains [22]. These methods are effective in handling the uncertainties related to the nZEB systems design. However, the degradation of the nZEB systems was neglected. A systematic way of investigating the degradation effects in nZEB systems and integrating these degradation effects into design is still lacking.

Degradation is prevalent in nZEB system components, from the chiller capacity, pump/fan efficiency in electricity demand side [16,23,24], to the efficiency of PV panels and wind turbine in the electricity supply side [25–27], and to the capacity of energy storage system [28,29]. Rosenthal investigated the performance of different PV systems and found that the degradation rates of 10 studied systems were larger than 1%/year [30]. The energy storage system capacity also degrades with its operation [28]. The degradation has a great influence on the system life-cycle performance. For instance, the degradation of chiller leads to decrease in the chiller maximum supply cooling capacity, which may result in inadequate thermal comfort during extreme hot weather conditions [16]. The efficiency degradation of PV and wind turbine leads to decrease in the annual power production [25,26],