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Life-cycle analysis of nearly zero energy buildings under uncertainty and degradation impacts for performance improvements

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Abstract

Sizing the nZEB systems properly is crucial for nZEBs to achieve the desired performances. The energy demand prediction uncertainties and the components' degradation are two major factors affecting the nZEB systems sizing. The energy demand prediction has been studied by many researchers, but the impacts of degradation are still neglected in most studies. Neglecting degradation may lead to a system design that can perform as expected only in the beginning several years. This paper, therefore, proposes an uncertainty-based life-cycle performance analysis (LCPA) method to study the impacts of degradation on the nZEBs longitudinal performance. Based on the LCPA method, this study also proposes a two-stage method to enhance the nZEB system sizing. The study can enhance the designers' understanding of the components' degradation impacts. Case studies show that an nZEB might not achieve zero energy targets after years due to degradation. The proposed two-stage design method can effectively mitigate this problem.

Keywords: Uncertainty; Near-Zero Energy Building; Degradation; Life-cycle Performance; Design

1. Introduction

Nearly zero energy buildings (nZEBs) are considered as a promising solution to mitigate the energy and environmental problem in the building sector. Until now, there are many policies and regulations established on nZEB for enhancing its application. For example, the European Directive on Energy Performance of Buildings

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announces requirements that all the new buildings should be 'nearly zero energy buildings' after 2020 [1]. The U.S. government sets a zero-energy target that 50% of commercial buildings should achieve by 2040, and 100% of commercial buildings should achieve by 2050 [2].

A proper sizing of nZEB systems is critical for nZEBs to perform as expected [3]. The uncertainties in energy demand prediction and the system components degradation are two major factors affecting the sizing of nZEB systems [4, 5]. The demand prediction uncertainties may easily result in oversizing of nZEB components due to over evaluation of the energy demand [3]. While components' degradation may lead to a design that cannot perform as expected during its whole service life [6].

For nZEB system design, uncertainties exist in the physical properties of building envelope, in the internal heat gain, in the weather condition, etc. [3, 7]. In recent years, many uncertainty-based design methods of nZEB systems have been developed [3, 7]. For instance, Hamdy et al. developed a three-stage optimization method to obtain the cost-optimal nZEB design considering uncertainty. In their method, the selection of passive building envelope and heat recovery measure is optimized in the first stage, the type of heating/cooling system is optimized in the second stage, and renewable energy system design is optimized in the third stage [7]. Yu et al. developed a nZEB system optimal design method based on genetic algorithm, which minimizes the initial investment and meanwhile satisfies the performance requirements under uncertainty [8]. These methods are effective in handling the uncertainties related to the nZEB systems design. However, the degradation of the nZEB systems was neglected.

Degradation is prevalent in nZEB system components [6]. Rosenthal found the PV systems efficiencies degrades at a speed faster than 1%/year [9]. The energy storage system capacity degrades with its operation [10]. The component degradation inevitably leads to performance degradation of the nZEBs. For instance, the degradation of renewable energy system efficiency (e.g. PV panel and wind turbine) would result in reduced power production [9]. The energy storage system capacity degradation would increase the interaction of nZEB and the grid, which threats the grid reliability and stability [10]. Consequently, sizing without considering the nZEB systems degradation might produce a design that does not perform as expected from a life-cycle aspect.

Considering the impacts of uncertainties and degradation, this paper proposes a life-cycle performance analysis (LCPA) method for investigating the longitudinal performance of the nZEBs. The objective is to improve the designers' understanding of uncertainties and degradation impacts on the system performance. Based on the proposed LCPA method, a two-stage design method is proposed to improve the sizing of the renewable energy systems and energy storage system. Case studies will be conducted to demonstrate the application of the LCPA method and the two-stage design method.

2. nZEB system design based on cooling demand uncertainty analysis and life-cycle performance analysis

2.1. Degradation model

This study uses the random deterioration rate method to model the degradation of nZEB system components. This method has a typical form shown in Eqn. (1), in which the average degradation rate is described using a fixed random quantity [11].

$$Q_t=Q_0\times(1-D_a t) \tag{1}$$

where D_a indicates the annual average degradation rate, t indicates the operation year, Q_0 indicates the amount when newly equipped (which can be energy storage system capacity, fan efficiency, WT efficiency etc.).

The quantification of degradation rate of PV panels and wind turbines can directly follow the existing studies [9, 12]. The degradation rate of energy storage system (i.e., an electrical battery in this study) can be calculated based on the Depth of Discharge (DoD) using Rainflow Counting Algorithm [10, 13]. Fig. 1 gives an example of the implementation of Rainflow Counting algorithm.

Step 1: Reduce the time-series DoD file to contain only valleys and peaks by identifying the reversal of the slop, see Fig. 1a and Fig. 1b.

Step 2: Determine two ranges R_1 and R_2 using three continuous points (*X(i), X(i+1), X(i+2)*) from the DoD files, as shown in Eqn. (2)

$$R_1=|X(i)-X(i+1)| \qquad R_2=|X(i+1)-X(i+2)| \tag{2}$$

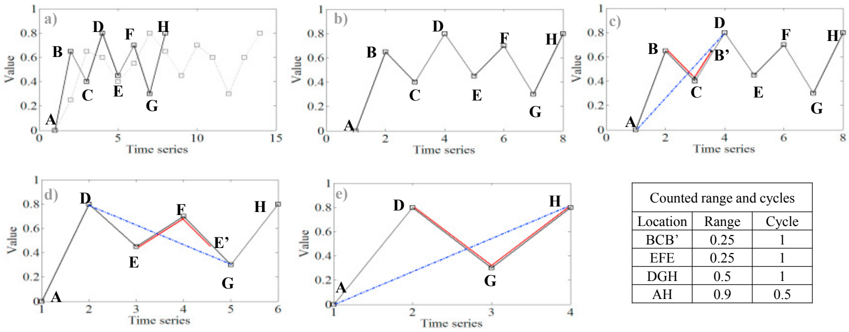
Step 3: Identified a cycle as a half (0.5) or full (1) cycle based on the rule presented in Eqn. (3),

$$Cycle = \begin{cases} 0.5, if\ R_1 \geq R_2, or\ i = 1 \\ 1, if\ R_1 \leq R_2 \end{cases} \tag{3}$$

Step 4: Repeat Step 2 and 3 to identify all the full cycles in the DoD file Step 2 and 3, and count R_1 as the ranges of the full cycles. Then discard the first and second point selected in Step 2, see Fig. 1c and Fig. 1d.

Step 5: Count all the three-point-series where R_1=R_2, identify them as full cycles, and remove the 1st and 2nd point after counting, see Fig 1e.

Step 6: Count each of the remaining range as a half cycle. (see Fig 1e). The identified ranges (R_k) and cycles of the example DoD profile are summarized in Fig. 1.



Location	Range	Cycle
BCB'	0.25	1
EFE	0.25	1
DGH	0.5	1
AH	0.9	0.5

Counted range and cycles

Figure 1 An example of conducting Rainflow counting algorithm

Using the ranges and cycles, the cumulative degradation rate is calculated by Eqn. (4) [13], where A and B are parameters that determine the DoD-Cycle curves.

$$D_{CL} = \sum_{k=1}^{m} \frac{Cycle\,of\ R_k}{A \times (R_k)^B} \tag{4}$$

2.2. Life-cycle performance analysis considering uncertainty and degradation effects

Fig. 2 presents the flowchart of LCP analysis under uncertainty and degradation impacts. The nZEB LCP is analysed by importing the uncertain inputs and degradation parameters into the nZEB and nZEB system model. In this study, EnergyPlus is used to simulate the performances of nZEB and HVAC system, Trnsys is adopted to simulate the performance of PV system and WT system, and Matlab is used simulate the electrical battery system operation.

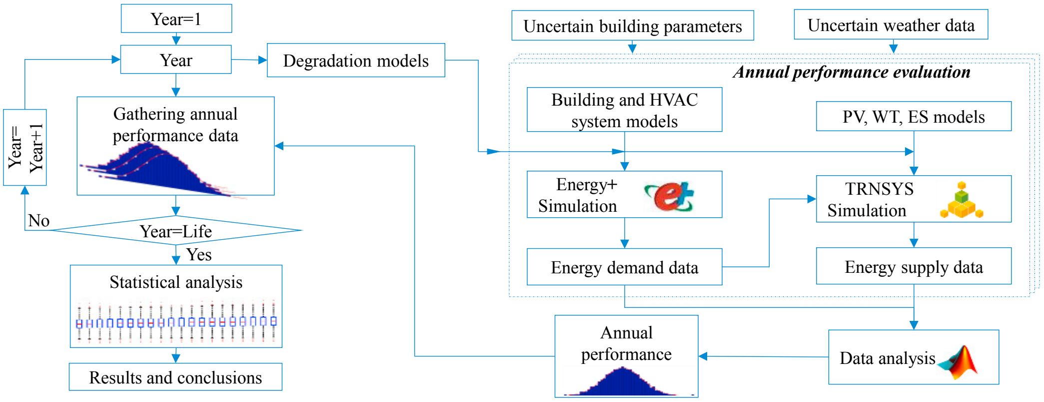


Figure 2 Process of ZEB LCPA under uncertain and degradation impacts

The LCP is analysed on an annual analysis. The simulation year begins from 1, and it is used as inputs in the degradation model to calculate the cumulative degradation in that year. The degradation terms, uncertain parameters and fixed parameters are used as inputs for predicting the annual performance. The annual performance data obtained from simulation will be stored in a database. The process repeats until the simulation year reaches the nZEB service life of. This study assesses four performance indices, (i.e., thermal comfort, energy balance, grid independence, and life-cycle cost).

2.3. A two-stage design method for enhancing nZEB sizing

Using the developed nZEB LCPA in Section 2.2, this section proposes a two-stage design method to enhance the nZEB system sizing, as illustrated in Fig. 3.

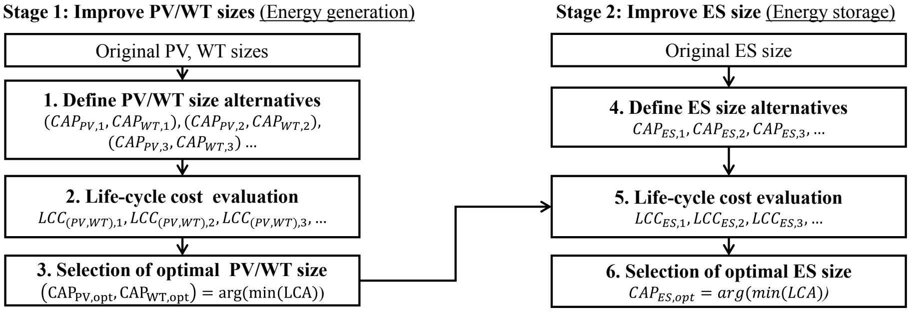


Figure 3 Flowchart of two-stage design method

At Stage 1, a number of PV/WT size alternatives are first produced based on the PV/WT size obtained under standard sizing procedure. Then, using the LCPA method developed in Section 2.2, the life-cycle cost of each PV/WT size alternative is evaluated. Note that the ES size obtained using the standard sizing procedure is fixed at Stage 1. Third, the life-cycle costs of all the alternatives are compared, and the one with the minimal life-cycle cost is considered to be optimal. Stage 2 has similar processes to Stage 1. A number of ES size alternatives are first defined based on the ES size obtained using standard sizing procedure, then the life-cycle costs of these alternatives are calculated and compared, and the one with the minimal life-cycle cost is selected as the ultimate optimal design.

3. Case studies

Case studies were conducted to demonstrate the procedures of nZEB LCPA, and application of the LCPA for enhancing sizing of nZEB systems. A case nZEB with a dimension of 25 m×25 m×3 m was built in EnergyPlus. The case nZEB was studied under Hong Kong weather condition. The nZEB is installed with an HVAC system, PV panels, wind turbines, and an electrical battery. The case nZEB is connected to the power grid. Only when the battery is fully charged/discharged, the nZEB would export/import energy to/from grid.

As in Hong Kong cooling is required during most time, this study mainly considered the cooling condition. The indoor air temperature and relative humidity were set to be 25℃ and 50%, respectively. Base on the setting, the average value of nZEB peak cooling load was calculated to be 279kW. Thus the HVAC system capacity was sized to be 279kW. The case nZEB has an annual electricity demand of 365,417 kWh. A simple configuration was used in this study, that the PV panels and wind turbines have the same amount of energy production. Using the standardized sizing method, the PV panel area was sized as 1298.6 m^2, and the required number of wind turbine was 16 (each wind turbine had a rated power of 30 kW), and the energy storage system capacity was sized as 1571.8 kWh.

3.1. Quantification of system degradation rates

Following literature [6, 9, 10], the annual degradation rates of HVAC system capacity, PV panel efficiency and wind turbine power production were quantified to be 0.25%, 1.3%, and 1.6%, respectively. The degradation rates of chiller COP and pumps and fans efficiencies were quantified to be 0.25%, 0.2% and 0.2% [6]. The degradation rate of energy storage system capacity was calculated to be 5.73% using the Rainflow Counting algorithm based on one-year operational data.

3.2. Life-cycle performance results

The case nZEB systems were assumed to serve for 30 years. In the simulation of each year, 100 samples were generated for each uncertain parameter using Latin Hypercube Sampling (LHS) method, thus the simulation repeats 100 times in each year (the simulation is conducted 3,000 times in total). Fig. 4 presents changes of the four performance indices over the period of 30 year. As can be seen from Fig. 4a, the average cooling set-point unmet hour increased 30% after 30 years. The annual operational cost increased from 60.7kHKD to 456.5kHKD (see Fig. 4b). The energy balance decreased from -0.03 to -0.63 (see Fig. 4c). The grid independence index dropped to 0 from 0.69 (see Fig. 4d). It's interesting that grid independence changed dramatically in the 18th year. This is because the energy storage system capacity already reduced to 0 (the battery average degradation rate was 5.73%). As a result, the nZEB will completely lose the ability of regulating unbalanced energy demand and supply after 18 years.

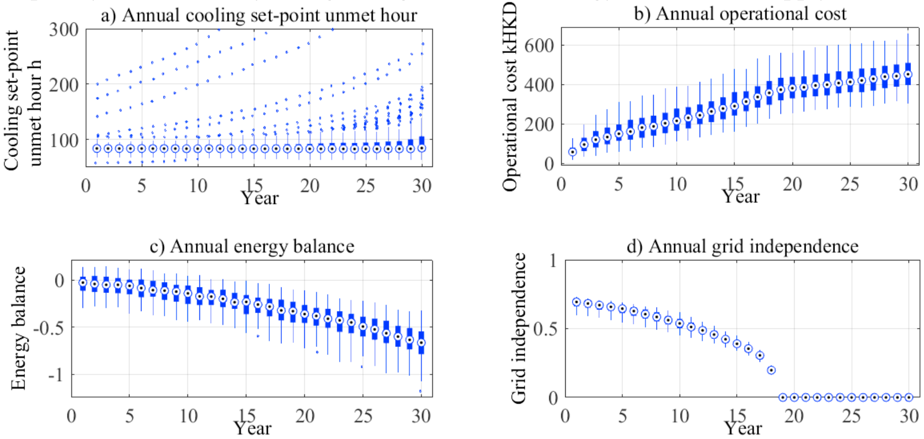


Figure 4 Varying of four performance indices with operating year

3.3. Performance improvements results using two-stage design method

Using the two-stage design method, the RES and ES sizes of the case nZEB were enhanced. In Stage 1, 17 options of wind turbine number were defined based on the standardized RES size (called Option 1). The number of wind turbine increased from 16 to 32 at an interval of 1. The PV panel area increases with the wind turbine number to produce the equal amount of energy. The energy storage system size was not changed. The life-cycle costs of the 17 options were calculated, as shown in Fig. 5a. As the wind turbine number increases, the life-cycle cost firstly decreased and then increases. The option of wind turbine number producing the lowest life-cycle cost was selected as Option 2. See Table 1 for detailed system sizes of Option 1 and Option 2. In Stage 2, the number of wind turbine and area of PV panels of Option 2 were considered as fixed inputs. A number of sizing factor options, ranging from 1 to 5 at an interval of 0.2, were defined for the ES size. The real energy storage system size is determined by multiply the sizing factor with 1571.8 kWh. Fig. 5b shows the changes of life-cycle cost with the energy storage system size. Again, the life-cycle cost of each option was analyzed and compared. The ES size option producing the lowest life-cycle cost was selected as Option. 3. See Table 1 for detailed system sizes of Option 3.

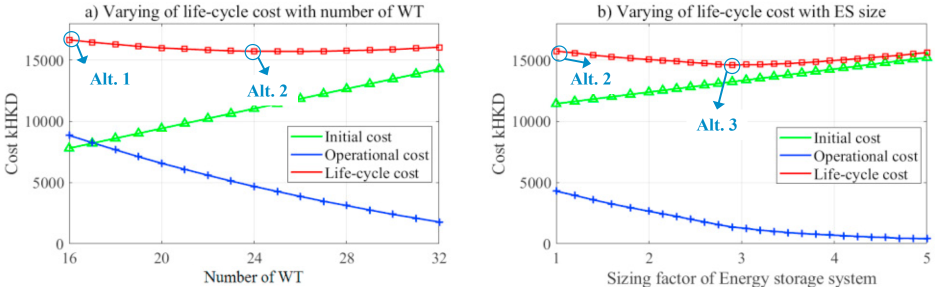


Figure 5 Results of performance improvements

Table 1 Summary of sizes of each alternative

Component	Size of each Option		
	1	2	3
WT (*each*)	16	25	25
PV panel (m^2)	1299	2029	2029
ES (kW·h)	1572	1572	4558

Table 2 Summary of LCC reduction from two-stage method

Stage	LCC (kHKD)			Reduced LCC	
	Option 1	Option 2	Option 3	Amount (kHKD)	Percentage
Stage 1	16,705	15,741	—	963.8	5.77%
Stage 2	—	15,741	14,599	1,142.3	6.84%
Sum				2,106.1	**12.61%**

Table 2 summarized the life-cycle costs of the three options, and presents the cost saving percentage. Stage 1 enhanced the sizing from Option 1 to Option 2 and achieved a cost saving of 5.77%. Stage 2 enhanced the design from Option 2 to Option 3 and further achieved a 6.84% saving. The two-stage method cuts down the life-cycle cost by 12.61% in total.

4. Conclusions

This study has proposed a life-cycle performance analysis method of nZEBs considering the impacts of uncertainties and components' degradation. The uncertainties in the energy demand prediction have been modelled by statistic distributions, and the nZEB system degradation has been modelled using random deterioration rate method. The proposed LCPA method can improve the designers' understanding of demand prediction uncertainties and components' degradation impacts on the nZEBs' performance. Based on the proposed LCPA process, this study also developed a two-stage design method to enhance the nZEB system sizing. Compared with the standardized sizing method, the two-stage method can produce a design that has better life-cycle cost performances (meanwhile achieve desired grid independence performance) from a life-cycle aspect.

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