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Design Optimization of Renewable Energy Systems in Low/Zero Energy Buildings Using Single and Multi-Objective Optimization Methods

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ABSTRACT

Low energy buildings and zero energy buildings have attracted increasing attention in both academic and professional fields following the ambitions of many governments in reducing building energy consumption and carbon emission. This paper presents an investigation on the optimal design of renewable energy systems in two types of buildings: low energy buildings and zero energy buildings. The first zero energy building in Hong Kong, namely Hong Kong Zero Carbon Building, is taken as a reference building in this study. The TRNSYS building model is used to generate the annual cooling load profile of the building. Simplified models are developed to simulate the building energy systems including the air-conditioning systems and the renewable energy systems in Matlab while the building annual cooling load profile is taken as the input. Genetic Algorithm method and Non-dominated Sorting Genetic Algorithm (NSGA-II) approach are implemented for single objective optimization and multi-objectives optimization respectively. Three most important design parameters, i.e., sizes of photovoltaic, wind turbine and bio-diesel generator, are chosen as the variables to be optimized. The performances of buildings, each with different combinations of renewable system sizes, are compared and evaluated.

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 (Kolokotsa *et al.*, 2011) and this percentage for building sector is even higher (over 90% of electricity) 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 (Crawley *et al.*, 2009). 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 [3]. Similarly, the Hong Kong government has set a target for carbon reductions: carbon intensity should be reduced by 50% to 60% by 2020 compared with 2005 baseline (Li, 2011). Over the last decades, increasing demos of zero energy buildings are developed all over the world (Minor and Hallinan, 2011; Fong and Lee, 2012; Marszal and Heiselberg, 2011; Bojic *et al.*, 2011). 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, ZEB researches have been mainly concerned with: different definitions and evaluation methods for ZEB (Marszal and Heiselberg, 2009; Hernandez and Kenny, 2010), building design and system configuration (Kibert, 2010; Robert and Kummert, 2012), demonstration of buildings integrated with renewable energies [Tiwari *et al.*, 2011; Nandi and Ghosh, 2010], design/management optimization (Thalfeldt *et al.*, 2013; Gamou *et al.*, 2002; Liu *et al.*, 2012). Increasing attention has been paid on how to design zero energy buildings in a cost-saving and environment-friendly way. Thalfeldt *et al.* (2013) 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.* (2011) 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 were mainly focused 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 emission and the negative impact of ZEB on electric grid reliability have not been taken into account in most studies. Therefore, multi-objective optimization may be a better approach to evaluate the ZEB's performance comprehensively. Effective optimization methods are essentially needed for optimal design of buildings and the energy systems. More than half of the works on building optimization concerned 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 (Evins, 2013). 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. And the most common optimization method implemented for multi-objective problems is non-dominated sorting Genetic Algorithm-II (NSGA-Ⅱ）(Deb, 2002).

This paper presents a simulation-based optimization method to optimize the design of the renewable energy systems size in two types of buildings: low energy building (LEB) and zero energy building revised on the basis of the Hong Kong Zero Carbon Building (ZCB). GA and NSGA-Ⅱ are used as the single objective and multi-objective optimization algorithms, respectively, to solve design problems of renewable energy systems. Case studies are conducted to evaluate the capability and effectiveness of two optimization methods, and to investigate the impacts of different combinations of renewable energy systems on the building performance.

2. OPTIMIZATION METHODS AND APPROACHES

2.1 Optimization approaches

In this study, the typical meteorological year 1987 of Hong Kong is set for annual building system simulation and the simulation time step is one hour. GA and NSGA-Ⅱare implemented to obtain the optimal renewable energy system sizes in low/zero energy building in Matlab 2006. In NSGA-Ⅱ optimization process, three objectives are set for both LEB and ZEB. For single objective optimization by GA, weighted-sum objective function (Eq-7) combining the three objective functions is minimized. The building model is firstly modeled in building energy simulation program – TRNSYS. The specifications of photovoltaic (PV), wind turbine, bio-diesel generator, the building and weather are provided for the building model and renewable energy system model. Occupancy schedule, lighting schedule as well as other equipment are set as that in the reference building (i.e. Hong Kong ZCB). Secondly, the building cooling load by TRNSYS simulation is provided for energy system models developed in Matlab. Then building electricity demand and energy generation are calculated using the energy system models. Finally the objective(s) is evaluated based on trial values of renewable energy system sizes (PV, wind turbine and bio-diesel generator). Using GA/NSGA-Ⅱ optimizer included in Matlab 2006, different trial values are searched and further applied for finding the optimal results. Fig 1 and Fig 2 show the schematic diagram of optimization procedures.

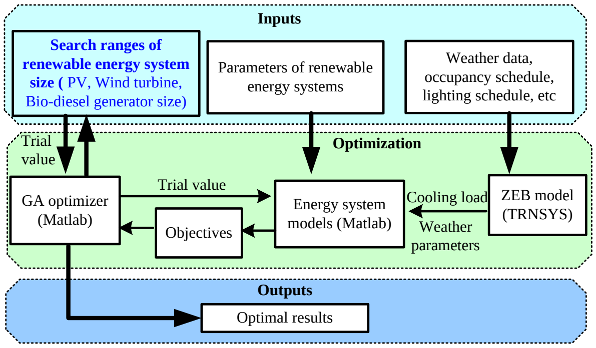


Figure 1: Design optimization using GA

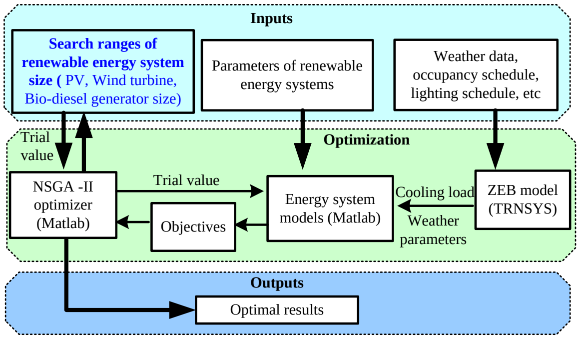


Figure 2: Design optimization using NSGA-Ⅱ

2.2 Objective functions

In the multi-objectives optimization, three objective functions are considered: total cost (TC), carbon dioxide emissions (CDE) and grid interaction index (GII). Total cost is the annually sum of building operational cost (oil cost and electricity bill cost) and renewable energy systems investment cost annually (the discount factor is not considered in this study).

Minimization of the annually total cost

$$Min\ TC = Cost_{resi} + Cost_{Operation} \tag{1}$$

Minimization of the total carbon dioxide emissions as follows. Where, CDE_e and CDE_{bio} are the emission factors for delivered electricity and bio-diesel generator on-site combustion respectively.

$$Min\ CDE = CDE_{electricity} + CDE_{BDG} \tag{2}$$

$$CDE_{electricity} = (P_{supply} - P_{export}) \times CDE_e \tag{3}$$

$$CDE_{BDG} = F_{bio} \times CDE_{bio} \tag{4}$$

The building-grid interaction, described in Eq-5, is based on the ratio between the exported and delivered energy compared to the average energy demand in the building during a given period. Grid interaction index (GII) is defined as the standard deviation of the building-grid interaction over the year as shown in Eq-6.

$$f'_{grid,i,T} = \frac{e_i - d_i}{\int_{t1}^{t2} E_i\, dt / T} \tag{5}$$

$$Min\ f_{gird,i,T} = STD(f'_{grid,i,T}) \tag{6}$$

Multi-objective optimization problems can be extended to single-objective optimization by using weighted-sum of various objectives, as shown in Eq-7. The sum of w_1, w_2 and w_3 is 1. The same building configuration after deleting all renewable energy systems is chosen as the “benchmark building” for normalizing objectives.

$$f = w_1 \times TC_n + w_2 \times CDE_n + w_3 \times f_{grid,i,T,n} \tag{7}$$

3. BUILDING SYSTEM CONFIGURATION AND ENERGY SYSTEM MODELING

3.1 Building system configuration

The energy systems studied are based on the system in the Hong Kong ZCB. Hong Kong ZCB covers a total land area of 14,700 m^2. It comprises of a three-story building with total floor area of 1,520 m^2. This building is integrated with various passive design (wind catcher, earth cooling tube, high performance glazing and ultra-low thermal transfer etc.), active design (high volume low speed fans, active skylight and high temperature cooling system etc.) and on-site energy generation systems (PV and bio-diesel generator).

Schematic of the studied building energy system and its integration with power grid are shown in Fig 3. Photovoltaic (PV) and wind turbine (WT) provide electricity. Bio-diesel generator can generate both electrical and thermal energy to meet building electrical load and cooling load. Typically, two basic operation strategies are widely used: Following the thermal load (FTL) and following the electric load (FEL) (Mago and Chamra, 2009). The operation strategy of following the thermal load (FTL) is applied in ZCB, therefore no heat production is wasted during the winter period when no cooling demand is needed. In this study, bio-diesel generator is controlled according to the building cooling load. When the cooling provided by the adsorption chiller (driven by bio-diesel generator) is not sufficient, the extra cooling load is undertaken by the electric chiller. If the by-product electricity generated by bio-diesel generator cannot meet the building electricity demand, additional electricity will supplied by the grid. The building electricity consumption comes from two parts: HVAC (fans, pumps, cooling towers and chillers) and other appliances (lighting, office equipment, etc.). The grid is the backup power supplier and receiver. The main parameters of energy systems are listed in table 1.

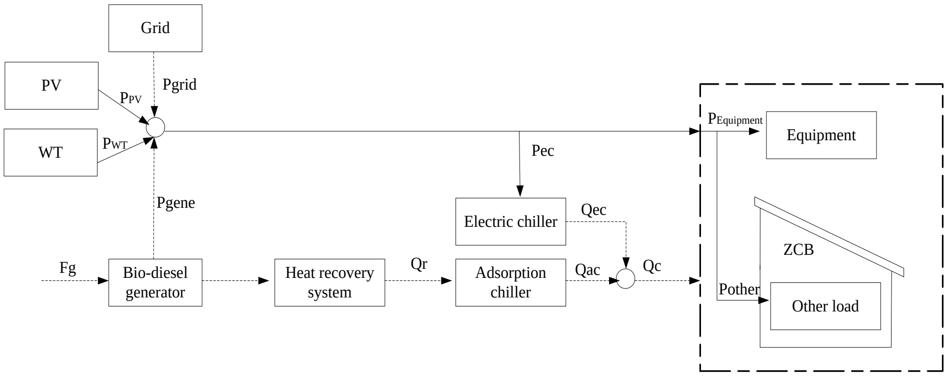


Figure 3: Energy flow relationship among the energy systems

Table 1: Basic data and energy systems parameters used in the study

Parameters	**Value**
Heat recovery system efficiency	0.8
BDG efficiency	0.3
COP_{ac}	0.7
Unit price of BDG (USD/kW)	205.53
Unit price for PV (USD/m^2)	378.17
Unit price for WT (USD/kW)	288.86
Oil price (USD/l)	1.3
Delivered electricity price (USD/kWh)	0.13
Exported electricity price (USD/kWh)	0.065
Lifetime for BDG (year)	20
Lifetime for PV (year)	20
Lifetime for WT (year)	20
A_G (l/kWh)	0.246
B_G (l/kWh)	0.08145

CDE_e	0.608
CDE_{bio}	0.552

3.2 Energy system models

In this study, the TRNSYS building model (TYPE56) is used to generate the building cooling load. Energy system models are developed in Matlab. Three types of renewable energy systems are installed in the building, including photovoltaic (PV), wind turbine (WT) and bio-diesel generator (BDG). The energy balance and simplified models of selected energy systems are described as follows.

i. Cooling demand

Cooling demand of the building is firstly satisfied by the adsorption chiller. When the building cooling load is less than the capacity of adsorption chiller, the total cooling load will be fully covered by the adsorption chiller. Otherwise, the remaining cooling load will be satisfied by electric chillers.

$$Q_c = Q_{ec} + Q_{ac} \tag{8}$$

ii. Electricity demand and supply

The electricity consumption/demand in this building comes from two sub-systems: HVAC and other appliances. The electricity demand is satisfied by the PV, wind turbine and bio-diesel generator, the power grid is assumed as an energy storage system to store surplus electricity or cover the power shortage.

$$P_{demand} = P_{supply} \tag{9}$$

$$P_{demand} = P_{HVAC} + P_{other} \tag{10}$$

$$P_{supply} = P_{PV} + P_{WT} + P_{BDG} + P_{grid} \tag{11}$$

In the HVAC system, the electricity is consumed by the electric chillers, pumps, cooling tower fans and AHUs. Simplified models of these components are built and the model parameters are identified using site measurements.

The PV power generation can be computed by Eq. (12) (Skoplaki and Palyvos, 2009; Kusakan and Vermaak, 2013a). Where A_{des} is the total area of PV (m^2). η_m is the module efficiency. P_f is the packing factor. η_{PC} is the power conditioning efficiency, I_{irra} is the hourly irradiance (kWh/m^2).

$$P_{PV} = A_{des} \times \eta_m \times P_f \times \eta_{PC} \times I_{irra} \tag{12}$$

Power generation from the wind turbine can be computed by Eq. (13) (Kusakan and Vermaak, 2013b; Ghedamsi and Aouzellag, 2010). Where ρ_a is the air density (kg/m^3), $c_{p,w}$ is the coefficient of the wind turbine performance, η_{WT} is the combined efficiency of the generator and wind turbine.

$$P_{WT} = 0.5 \times \rho_a \times A_{WT} \times v_{wind}^3 \times c_{p,w} \times \eta_{WT} \tag{13}$$

Power generation by the bio-diesel generator depends on the heating needed by the adsorption chiller, as shown by Eq. (14) (Mago and Hueffed, 2010). The fuel consumption is estimated by Eq. (15) (Ismail *et al.*, 2012). Where, Q_r is the waste heat from BDG. η_{BDG} and η_{hrs} are the efficiencies of the BDG and the heat recovery system respectively. P_{BDG} and $P_{rated\text{-}BDG}$ are the actual power output and the rated power of the BDG respectively

$$P_{BDG} = \frac{Q_r}{(1-\eta_{BDG})\times\eta_{hrs}} \times \eta_{BDG} \tag{14}$$

$$F_{bio} = A_G \times P_{BDG} + B_G \times P_{rated-BDG} \tag{15}$$

The power grid can be treated as a backup power supplier and receiver for the building depending on the building power demand and renewable energy generation as shown by Eq. (16).

$$P_{grid} = P_{HVAC} + P_{other} - (P_{PV} + P_{WT} + P_{BDG}) \tag{16}$$

$P_{grid}>0$ represents the grid supplies electricity for the building. $P_{grid}<0$ means the building exports surplus electricity to the power grid.

4. RESULTS AND ANALYSIS

The following two cases studies were conducted to investigate the effects of the single objective optimization using GA and multi-objective optimization using NSGA-Ⅱ on the sizing of renewable energy systems. *Case1*: Optimal design for two types of buildings (LEB and ZEB) using single objective optimization approach; *Case 2*: Optimal design for two types of buildings using multi-objective optimization approach.

4.1 Case 1

The results of optimal renewable energy system sizes for the two types of buildings using GA approach are summarized in Table 2. The WT size ranges between 0 and 40 kW. The BDG capacity ranges between 50 and 150 kW. The PV area ranges between 500 and 1500 m^2. The Hong Kong Zero Carbon Building after deleting all renewable energy systems is used the “benchmark building” (BB) in this study. The different weighting factors may be selected in different situations and usually determined by the user requirements. In this case study, four tests (A, B, C, D) based on different weighting factors were investigated and compared. In the Test A, the three objectives are treated equally in both of LEB and ZEB. In each of the other three Tests, only one of the objectives is concerned. The test results show that the optimal objective value is less than 1 in the Test A. When only the total cost is concerned in Test B, the optimal objective value is close to 2 due to the high investment cost of renewable energy systems. However, the performances of LEB and ZEB in Test C and D are much better than that of BB (benchmark building) when priority is put on the reduction of CO_2 emission or grid interaction index. It is interesting to note that the optimal objective value of LEB is negative in test C. It means that in a comprehensive view, CO_2 emission from power grid and bio-diesel combustion is offset by that from surplus power generation in the building.

Table 2: Optimal RES sizes for buildings using GA approach (Case 1)

Test No.	Weighting factors w_1, w_2, w_3	LEB WT *(kW)*	LEB BDG *(kW)*	LEB PV *(m^2)*	LEB Minimum objective value	ZEB WT *(kW)*	ZEB BDG *(kW)*	ZEB PV *(m^2)*	ZEB Minimum objective value
A	1/3, 1/3, 1/3	33.9	50.0	500.2	0.82	40.0	50.1	458.3	0.82
B	1, 0, 0	20.8	50.0	500.0	1.90	40.0	50.0	462.7	1.83
C	0, 1, 0	40.0	97.6	1493.9	-0.46	0.8	50.0	1237.6	0.13
D	0, 0, 1	0.0	50.0	500.0	0.32	23.4	52.1	699.7	0.45

Figure 4-6 present the comparisons between the total cost, CO_2 emission and grid interaction index of the three buildings (BB, LEB, ZEB) in four tests. As shown in Figure 4, the total costs of both LEB and ZEB in all tests are much higher than the cost of BB. Particularly in Test C, the total cost in LEB is nearly 3 times of that for BB. In Figure 5, CO_2 emissions of LEB and ZEB reduce dramatically compared with the CO_2 emissions of BB and even become negative (i.e., LEB in Test C). Figure 6 shows that both the grid interaction index (GII) of LEB and ZEB are much smaller than that of BB in most tests (A, B and D). Meanwhile the grid interaction index of LEB can be higher than that for BB in test C. In the situation of LEB, higher cost results in lower CO_2 emission but higher grid interaction index, while in the situation of ZEB, the cost, CO_2 emission and grid interaction index have less fluctuation.

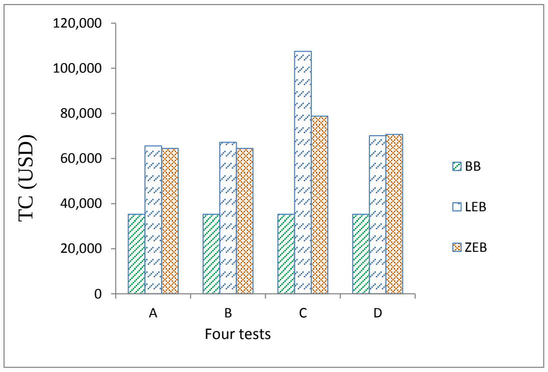


Figure 4: Total cost (TC) of four tests

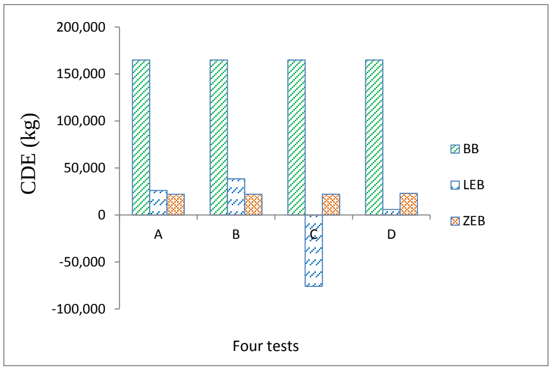


Figure 5: CO_2 emission (CDE) in four tests

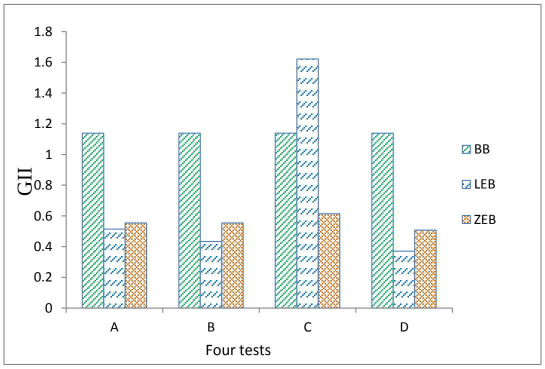
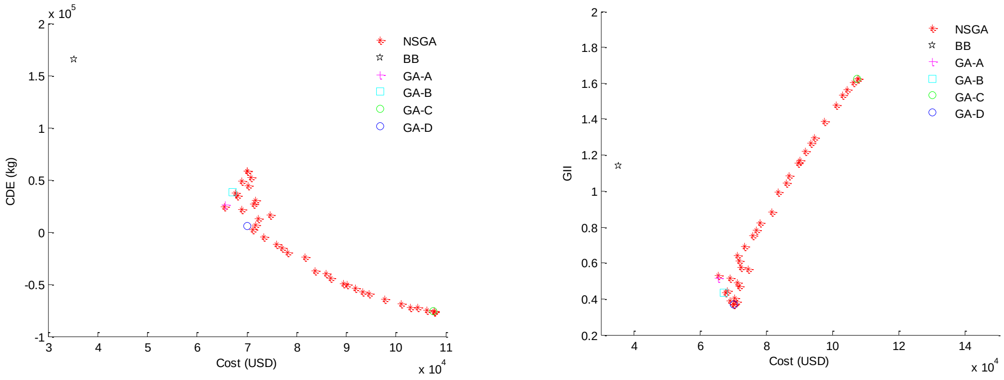


Figure 6: Grid interaction index (GII) in four tests

4.2 Case 2

The NSGA-II approach is applied to optimize sizes of the same renewable energy systems of LEB and ZEB while the searching ranges are set to be the same as that in Case 1. The best pareto-front sets obtained are shown in Figure 7. It also illustrates the diversity features of NSGA-II in contrast with the optimal results in Case 1. With regarding to LEB, minimization of total cost naturally requires to reduce the investment of renewable energy systems. Because of the reduction in the renewable energy system investment, the corresponding electricity needed from the grid increases resulting in the increase of CO_2 emission dramatically. It is obvious that the two objectives (i.e. total cost and CO_2 emission) are contradicting with each other. The reduction of renewable energy system investment results in smaller electricity flow between the building and grid and therefore lower grid interaction index. This agrees with the results in Case 1 using GA optimization.



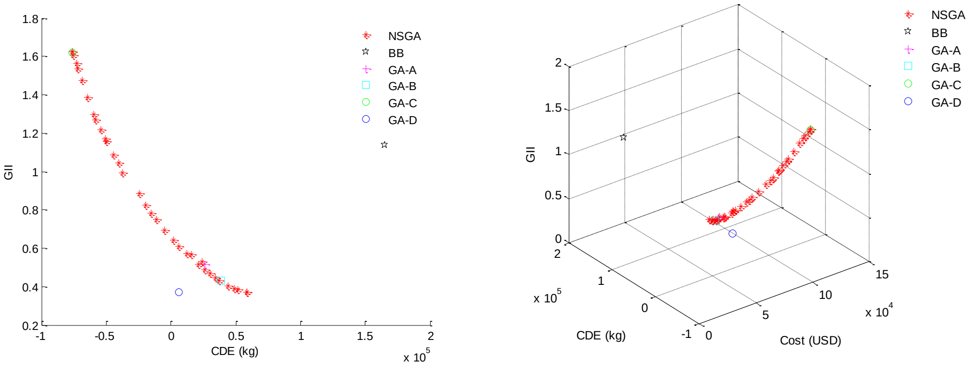


Figure 7: The pareto-optimal sets in two-dimensional and three-dimensional objective spaces for LEB

In the situation of ZEB, it is observed that the minimization of total cost result in smaller changes in CO_2 emission, showing a different trend compared with that of LEB. This is because in the obtained 35 pareto-optimal sets in ZEB, BDG size is kept between 50 kW and 52 kW. Therefore, CO_2 emission, mainly coming from related oil consumption from BDG, has less changes since the electricity from/to grid is balanced anually in ZEB. The performance of BB and ZEB in four tests by GA are labeled in Figure 8. It is obviously that GA-A and GA-B have priority than GA-C and GA-D regarding the cost and CDE. GA-C is not a good choice, since it cost higher with higher grid interaction index but has less benefit on CO_2 emission reduction.

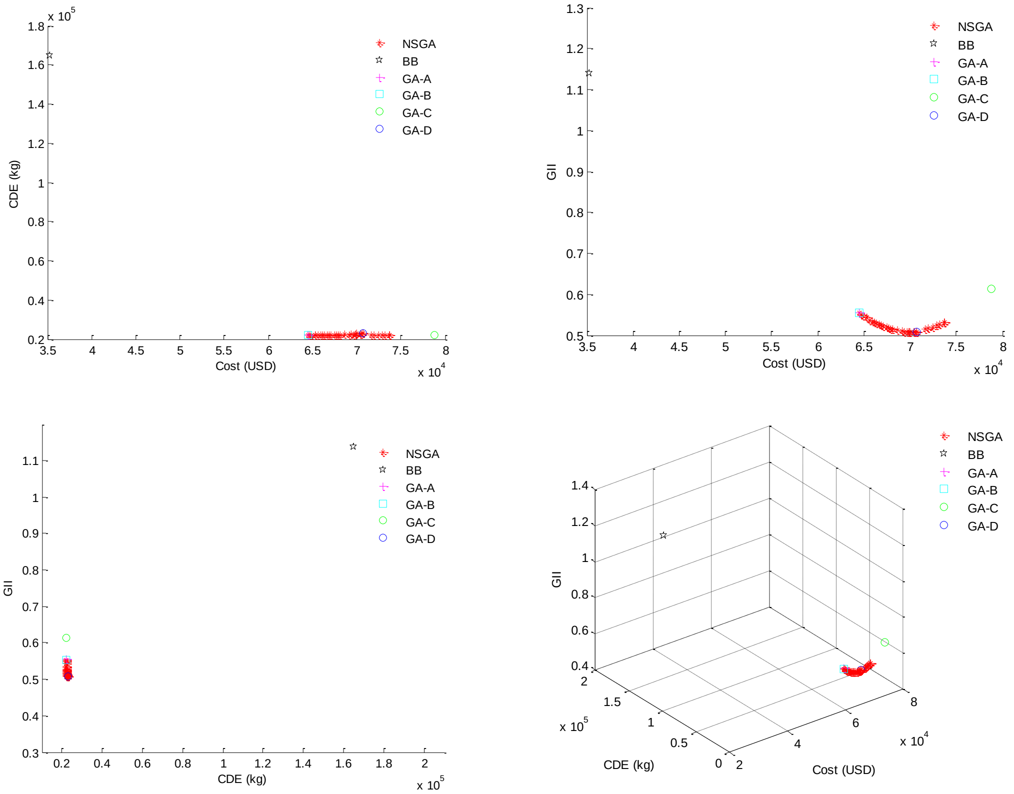


Figure 8: The pareto-optimal sets in two-dimensional and three-dimensional objective spaces for ZEB

5. CONCLUSION

In this paper, the investigation on the optimal design of renewable energy systems in low/zero energy buildings is presented. Simulation-based optimization is applied to optimize the renewable energy system sizes in the buildings using Genetic Algorithm (GA) method and non-dominated sorting Genetic Algorithm-Ⅱ (NSGA-Ⅱ) approach for single objective optimization and multi-objectives optimization respectively. Study shows that, when three objectives are of concern, it can be handled as a single objective optimization problem by lumping the three objectives into one. Although the “best” solution can be given directly, the designers are not given any information on the effects of parameters to be optimized on different design objectives. The multi-objective optimization by concerning the total cost, CO_2 emission and grid interaction index in parallel, provides rich and valuable information on these effects to decision makers, allowing them to find one or more appropriate compromised solutions from the sets of pareto-solutions obtained.

Two case studies were conducted to investigate the effects of two optimization methods on the optimization outputs. The results of single objective optimization show that the total cost of low/zero energy buildings equipped with renewable energy systems is 2 to 3 times of that for benchmark buildings in all situations investigated. Large renewable energy systems could even achieve negative CO_2 emission which is positive for environment conservation. The grid interaction between zero/low energy buildings and the grid could be reduced since electricity generation results in less building dependence on the grid. In multi-objective optimization, three objectives (i.e. total cost, CO_2 emission and grid interaction index) are considered in parallel. From pareto-optimal sets generated by the optimization, it is observed that, with respect to the low energy buildings, the minimization of the total cost requires the reduction of investment the renewable energy systems, resulting in higher CO_2 emission and lower grid interaction index. Concerning the zero energy buildings, the CO_2 emission and grid interaction index have less fluctuation as the changes of total cost.

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