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Energy System Design and Optimization of a Solar Decathlon House

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Abstract

In architectural design, solar energy building has become the focus of many architects. In order to achieve the expected energy efficiency, the appropriate energy system should be configured during the design phase in accordance with the idea of building integrated design. In this paper, a house was designed for Solar Decathlon competition 2017 in China. In order to reach the target of energy balance, the design team employed BIPVs, solar heating system and several energy efficient technologies. By the use of simulation-based method, the energy system of the house was designed and optimized, so that the house can meet the requirements of "passive building" completely with reasonable building design and energy system configuration. The optimal design method described in this paper can provide effective solution and practical reference for the design of solar energy buildings.

Keywords: Solar energy house, Energy system, Building integrated design, Simulation-based method, Optimization

1. Introduction

Here introduce the paper, and put a nomenclature if necessary, in a box with the same font size as the rest of the paper. The paragraphs continue from here and are only separated by headings, subheadings, images and formulae. The section headings are arranged by numbers, bold and 10 pt. Here follows further instructions for authors.

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Solar Decathlon China 2017 is the competition to present the effectiveness of exemplary energy efficiency houses. As one of teams in Solar Decathlon China 2017, Team TJU-TUD (Tongji University and Technische Universitat Darmstadthas) submitted the design, the EnergyPLUS Home 4.0. Beyond the north and south facades which already have perfect thermal performance, there are two buffer zones added to make the home perform better both technically and architecturally. The zones could act as climate buffer layers in cold winter and even winter gardens when there is comfortable sunshine. In summer, the windows could be open, and then ceilings on south buffer zone turn to be sun-shading panels. In transfer seasons, people could directly go out and sitting, reading, or enjoying their coffee on the balconies, then the zones would be additional space just to enlarge the area. Besides the buffer zones which could be built on site, the main part structure would be made of 12 prefabricated steel boxes, let the function even more flexible and the whole construction process more sustainable.

Fig. 1. The renderings of EnergyPLUS Home 4.0.

The competition is an award-winning program that challenges collegiate teams to design, build and operate solar-powered houses that are cost-effective, energy-efficient and attractive [1]. In general, the energy balance is required to be struck in the competition [2], which means that the solar energy plant on the house can produce at least as much electrical energy as is consumed during contest week. Another goal to be achieved is higher energy generating capacity, with which the more electrical energy generated per unit PV area, the more points earned [3]. After the contest week finishes, the building which gets most points will win the competition. Thus it is important to design and optimize the energy system for the solar energy house.

2. Methods

The method is based on simulation [4, 5]. To build the model, the certain climate of the building site, Dezhou, Shandong province, where the competition will be held, is needed. The hourly TMY (Typical Meteorological Year) data of Dezhou is used for detail energy simulation of the specific house *EnergyPLUS Home 4.0.* And the geographic information about Dezhou, is also presented in the climate data, whose latitude is N37.43, longitude is E116.32, and elevation is 22m. Therefore the angles between sunlight and the surfaces of the house hourly can be calculated [6].

Fig. 2. Zoning in building geometric model, F1 (left), and F2 (right).

The geometric model of the house is built in DesignBuilder environment, which is based on EnergyPlus engine [5]. The building geometric model can be built with this tool, which can export into idf file, for being read by EnergyPlus to develop energy analysis. In energy analysis model, in order to calculate the load and size the HVAC terminals, the house is divided into 10 zones. Fig. 2 illustrates the schematic for zoning. The first floor is divided into 5 zones as a living room, a dining room, an equipment room, and two buffer zones at the first floor. And the second floor is also divided into 5 zones, as two bedrooms, a corridor, and two buffer zones at the second floor.

There are several types of materials can be embedded in the envelope as a layer of insulation, such as extruded polystyrene board (XPS), urea formaldehyde foam (UFF), glass wool and so on. However, during the production process of XPS and UFF, byproducts of plastic foam will be produced, which can do harm to environment [7]. For green spirit in construction, it is determined to use glass wool between the OSB (Oriented Strand Board) panels as main structure instead of XPS or UFF. Thus the envelope construction of the house is decided under the cooperation between architects and engineers of the team. (Table 1)

Table 1. The structure of the exterior walls of the house from outside to inside.

Type	Thickness [m]	Conductivity [W/(m.K)]	Density [kg/m3]	Specific Heat [J/(kg.K)]
Gypsum plastering layer	0.005	0.4	1000	1000
Weber.therm RS 021 Fassade plus ultra	0.2	0.025	35	1400
OSB panel	0.012	0.14	650	1200
Glass wool	0.05	0.04	30	840
OSB panel	0.012	0.14	650	1200
Air layer	0.044	0.023	1.20	1004
OSB panel	0.012	0.14	650	1200

Besides, Table 2 and Table 3 show other parameters like window structure, lighting load, equipment load, and occupants used in model, provided by other group of the team. It is noted that the curtain will work when indoor air temperature is higher than 26 ℃.

Table 2. The structure of the windows of the house from outside to inside.

Type	Thickness [m]	Conductivity [W/(m.K)]	Solar Transmittance	Solar Reflectance	Infrared Emissivity
low-e glass	0.005	0.8	0.837	0.075	0.84
argon layer	0.006				
low-e glass	0.005	0.8	0.837	0.075	0.84
argon layer	0.006				
low-e glass	0.005	0.8	0.837	0.075	0.84
curtain			0.15	0.84	0.74

Table 3. The parameters set in simulation model.

Type	Data
Lighting	6 W/m2
Equipment	5 W/m2
Occupant	4 persons
Air changes	1 h-1

3. Results and Discussion

3.1. Buffer zone analysis

Two buffer zones with three-layer low-e glass outwards windows are designed at both the south side and the north side of the house, which function as the transition rooms between indoor area and ambient environment. These two zones are not controlled by HVAC system in summer and winter, but introduce natural ventilation and daylighting into the house (Fig. 3).

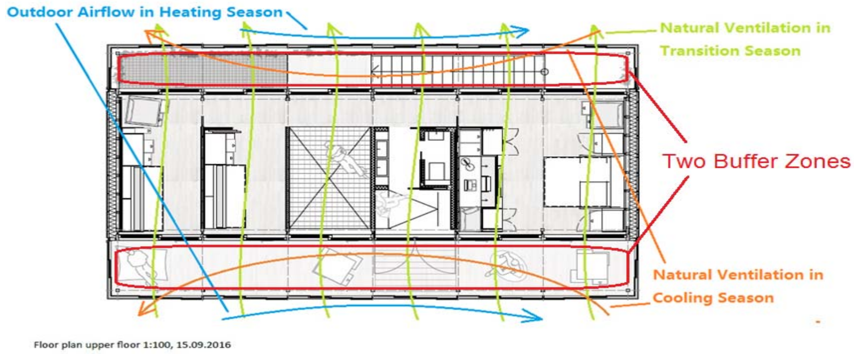

Fig. 3. The top view showing the ventilation principles of windows.

During cold days, all windows are closed and these two zones will be much warmer than outside just like a greenhouse. When during severe cold day people don't use these two zones, the much higher temperature than outside of the air in these two zones can reduce the heating load in winter. During hot days, all windows are open, which makes these two zones the same as outside by natural ventilation. In other words, when during severe hot day people also don't use these two zones, with the roof of these two zones serving as the external shading.

Considering the fluctuation of temperature in buffer zones, indoor decoration materials with phase change materials (PCM) may be used to assist in improving the condition. When transferring from solid to liquid PCM absorbs a large amount of heat, and when transferring from liquid to solid it releases. It means that by utilizing the solidification heat or fusion heat some heat gain at hot time can be move to raise the temperature of the same zone at cold time during one day [8]. Then the highest temperature in one day will be lower and the lowest will be higher, and thus the peak heating load and cooling load are both reduced.

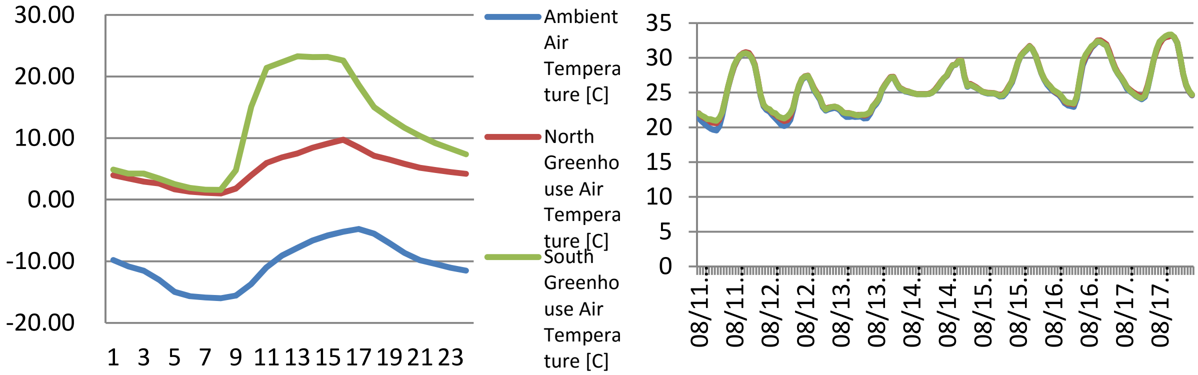

Fig. 4. Dry-blub air temperature in buffer zones on winter design day (left) and in contest week (right).

In this design, PCM will be set at appropriate places in the ceilings and floors of the buffer zones, and then it can make the greenhouses warmer than before at night when there is no sunlight going through the windows. The original design with passive technology will contribute to lessen the HVAC load and energy consumption of the house.

The effect of buffer zones warming in winter can be indicated in simulation, whose modeling periods are Jan 5th, the winter design day in typical meteorological year (TMY), and Aug 11th to Aug 17th, the week of competition time. The parameter inspected is dry-bulb air temperature in buffer zones, as shown in Fig. 4, which indicates that the design can make buffer zones much warmer than outside in winter and trap no more heat from sunshine in summer due to the opening windows making buffer zones the same as outside. It is also the reason why no explicit temperature difference between the results in contest week.

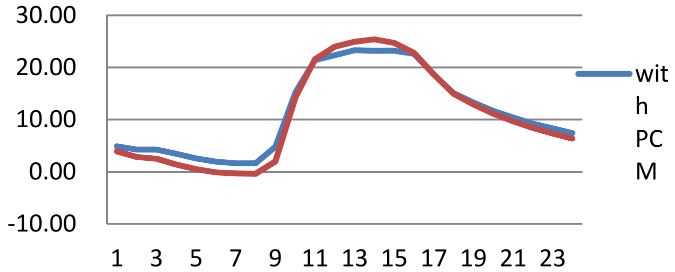

Fig. 5. Dry-blub air temperature in buffer zones with PCM on winter design day.

Fig. 5 shows that the PCM embedded in ceiling and floor of buffer zones is also able to work for ameliorating condition of buffer zones, which absorbs heat when hot and releases when cold. It alleviates the severe temperature condition in these two buffer zones.

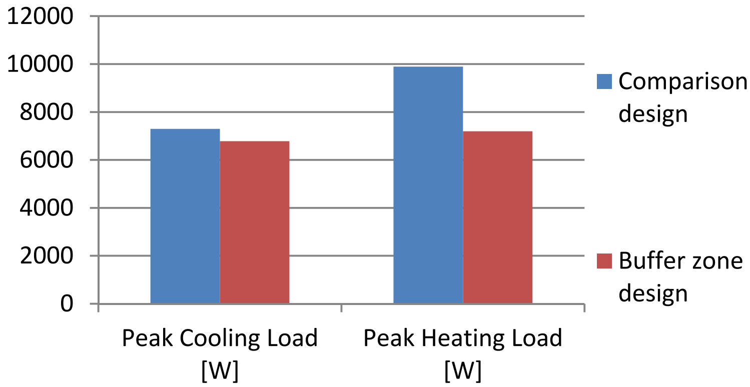

Fig. 6. The comparison between the peak HVAC loads of two designs.

To demonstrate the ability that these two buffer zones reduce the heating load in winter and transition seasons, we made the comparison of HVAC load between the house and another imagined house with only controlled zone, which contacts outside instead of buffer zones. Fig. 6 shows that in winter the buffer zones can meet part of demand for heating, especially at the south side, and for a summer week of contest time, with all windows opening the buffer zones can lessen the cooling load of HVAC system slightly, serving as the exterior shading.

3.2. HVAC system solution

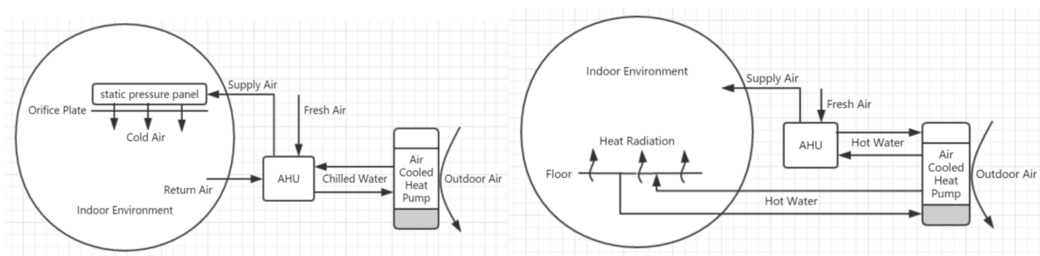

Fig. 7. The operation principles of selected HVAC system.

After load calculation, the HVAC system design can be solved. Fig. 7 shows the basic principles of the HVAC system, whose terminal devices are the type as describes below: orifice plate air supply on the ceiling (when cooling), baseboard radiant heating & DOAS (when heating). To ensure the high quality of fresh air, there is a filter at the entrance of AHU. Cooling and heating source is an air cooled (source) heat pump, whose COP when cooling is 5.3 for cooling and 4.2 for heating (Table 4). It's assumed that all hot water from PT system is not used for HVAC system. On some severe cold days, the ambient temperature is very low and thus heat pump can't work efficiently, when electric auxiliary heat has to be implemented.

Table 4. Parameters of heat pump in simulation model.

Cooling Capacity [W]	Heating Capacity [W]	Peak Cooling Load COP	Cooling Power [W]	Peak Heating Load COP	Heating Power [W]
6782.89	7192.45	5.0	733.78	1.8	1349.08

3.3. Solar energy collector analysis

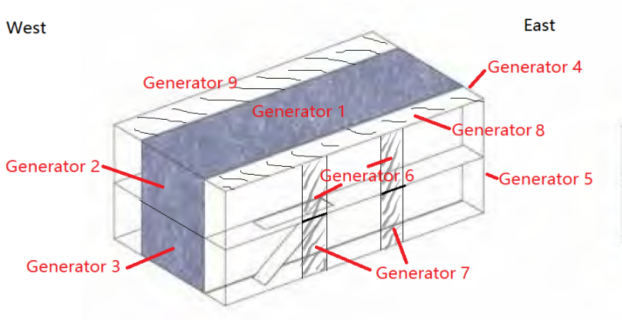

Fig. 8. Sketch to show the position to set PV devices.

Solar energy collector considered to be set consists of PV (photovoltaic) device and PT (photo-thermal) device [9, 10]. We firstly assume that all solar energy collector devices are PV panel in modeling. For model to be calculated, the geometric parameters are needed. Figure 8 shows the position and the name in model of each collector on the house, among which generator 1 is on the roof of control zone, generator 2 and 3 are on the 2nd and 1st floor west facade, generator 4 and 5 are on the 2nd and 1st floor east facade, generator 6 and 7 are on the 2nd and 1st floor south facade, and generator 8 and 9 are on the roofs of south and north buffer zone. And a typical PV panel usually has the performance data as shown in Table 5. We use a relatively lower conversion efficiency for calculation so as to ensure the energy get from the PV panel is enough even when the weather is not very good.

Table 5. Parameters of PV devices in simulation model.

Type	Data
Photoelectric conversion efficiency	14%
DC to AC Inverter Efficiency	80%
Schedule	Always On

To determine which surface should be used to collect solar energy to get the best efficiency, the selected 9 assumed PV panels (Fig. 8) are modeled. The simulation results can tell us which part of facades and roof should be covered with PV panel and which part better not. Fig. 9 shows the Electricity per area produced by every PV panel during competition time, which indicates that only use the roof of the building to set PV devices (Generator 1, Generator 8 and Generator 9). Besides, the PV panels on the roof of the control zone are opaque, and those on the roof of the buffer zones are in the semi-transparent glass with 70% absorption to keep the day lighting in the house.

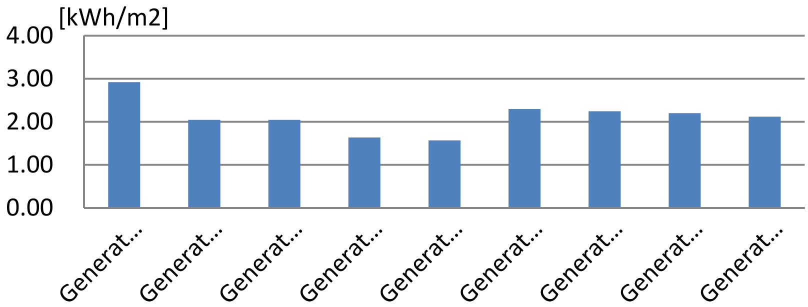

Fig. 9. Electricity per area produced by every PV panel during competition time.

For other facades with low PV efficiency, PT device can be equipped to supplement hot water to building water system in order to collect solar energy as much as possible. PT devices are used to get thermal energy to produce hot water for daily life with a heat retaining water tank. The efficiency of PT devices is set to be 70% in modeling.

Table 6. Parameters of PV devices in simulation model.

Type	Energy Consumption [kWh]
Equipment	87.28
HVAC System	135.78
Total without Hot Water	223.06
Hot water	141.56

To ensure that the total energy producing devices should generate sufficient energy for the house during the competition time, the energy balance of the house should be discussed. The contest time lasts from Aug 11th to Aug 17th. According to climate data, the HVAC system should work on cooling mode for the whole time. All energy consumption during the same time is acquired according to the data from water design group and electricity group. (Table 6)

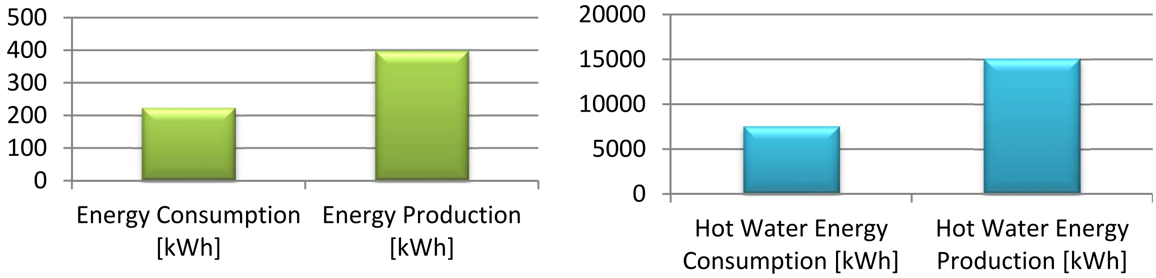

Fig. 10. Energy balance comparison of, electricity (left), hot water (right).

Fig. 10 indicates that the electricity generated by PV panel can cover energy consumption in ideal condition, even ignoring the heat gain from PT devices. The large margin can assure using if the sky clearness is not good while the house is working. For PT devices, the thermal energy they collect is also sufficient to supply hot water for residents with amount of margin.

4. Conclusions

According to the requirements of the solar decathlon house in the contest, the application of passive energy efficiency technology on the house and the validation of its effect are researched by model-based methods. The results show that some passive technologies are effective and feasible for the design. Based on the modeling, the architectural design was improved and perfected, and the design of the air-conditioning system was also carried out.

Moreover, in this paper the study and optimization of the energy system configuration of the solar energy building are also done according to the actual situation. The conclusion is that the total electricity consumption of the house can be satisfied by the solar photovoltaic system, and that all the hot water demand can be satisfied by the solar thermal system. With the reasonable building design and energy system configuration, the house can meet the requirements of passive building completely. Therefore, the research on the integrated building design and energy system configuration in the paper can provide effective design ideas for such solar energy buildings, and also practical case for the application of building energy efficiency technology.

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