Simulation Application in Evaluation of Zero Energy Building: Case Study

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ABSTRACT

In addition to experiment, simulation is an important tool to assist the evaluation of high performance buildings and associated energy systems. An experiment-verified system simulation model, which describes the couple operation between the building and its on-site energy system, can repeatedly and quickly supply operation performance data in an acceptable error range for the entire year, even the whole life time, under different external conditions. Zero energy building (ZEB), which is considered to be an integration solution to address problems of energy-saving, environment protection, and CO_2 emission reduction in the building section. The critical evaluation indicator for ZEBs is an annual energy balance between delivered energy from grid and renewable energy generation and this evaluation indicator can be realized by an experiment-verified simulation system. A case study is present in this article to show possible simulation applications in evaluation of ZEB in terms of simulation-assisted design, simulation verification and simulation-assisted evaluation. The evaluation results show that the studied ZEB consumes 3335 kWh per year which can be offset by a 24 m^2 kW PV array under a typical Chinese life style in Shanghai. With the assistance of simulation, the evaluation results prove that the zero energy aim can be achieved and also show that indoor temperature comfort can be kept during 94.4% occupant time.

KEYWORDS

Net zero energy, building efficiency, evaluation, life cycle, solar energy

1. INTRODUCTION

Because of irreversibility during the construction process, building design and evaluation is more and more depended on simulation technology. Design results of National Stadium (Nest) and National Swimming Centre (Water Cube) which are two landmark buildings of 2008 Beijing Olympic Game are both verified by simulation technologies (Mao, 2008, Chow, et al., 2009). An experiment-verified system simulation model, which describes the couple operation between the building and its on-site energy system, can repeatedly and quickly supply operation performance data in an acceptable error range for the entire year, even the whole life time, under different external conditions. In recent year, the research about zero energy building (ZEB) was definitely facilitated by the simulation, because critical evaluation

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indictor for ZEBs is an annual energy balance between delivered energy from grid and renewable energy generation, which can be realized by an experiment-verified simulation system.

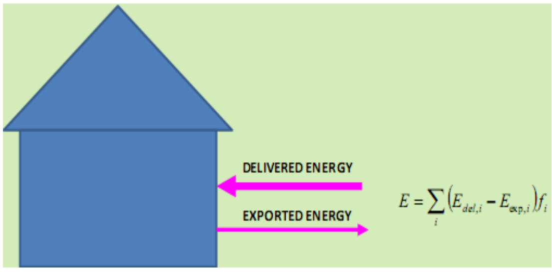


Figure 1. *Model of ZEB definiation (Kurnitski et al, 2011)*

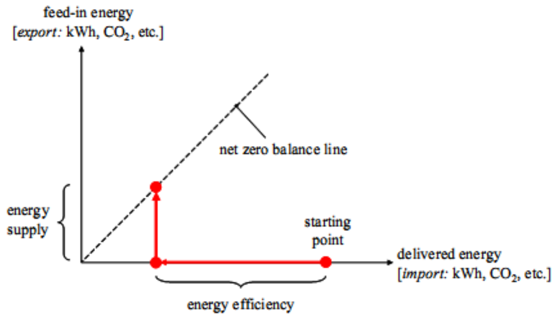


Figure 2. *Graphical definition of ZEB (Satori et al, 2012)*

$$\begin{aligned} Net\ Energy &= /weighted\ supply/ - /weighted\ demand/ \\ &= \sum_i delivered\_energy(i) \times credits(i) - \sum_i feed-in\_energy(i) \times credits(i) \\ &\geq 0 \end{aligned} \tag{1}$$

US Department of Energy (D.O.E) has presented a comprehensive definition which covers four kinds of ZEBs and their boundaries and metrics (Crawley et al., 2009). Satori et al (2012) discussed the criteria for definition of ZEB and presented a simplified mathematical equation to describe the definition, which is shown as equation (1). REHVA Task Force also uses a similar mathematical definition, as figure 1 shown (Kurnitski et al, 2011). These expressions are easy to be understood that the balance between weighted demand and weighted supply over a period of time should be zero, even positive, when the boundary of building zone is fixed. It can be expressed mathematically as is shown in equation (1). The boundary, period, credit (or called energy form), depend on designer's different purposes and not be limited to a constant form. This mathematical definition can also be presented graphically, as is shown in figure 2. The starting point on the x-axis of delivered energy represents a building built according to the minimum requirements of the local building code. By means of energy efficiency measures, energy demand was reduced to a low level. Then enough credits, such as an amount of electricity generation, primary energy, CO_2 emission reduction, are obtained by various renewable power supply options. In this case, the energy balance can be achieved. REHVA also proposes a technical definition for nearly zero energy buildings required in the implementation of the Energy performance of buildings directive recast.

In this article, we choose the definition of net zero site energy from D.O.E, which means a site ZEB produces at least as much renewable energy as it uses in a year, when accounted for at the site. So the boundary is limited in the building footprint; the period is annual; the energy used is for maintaining energy of HVAC, DHW etc in a basic analysis of energy balance, while in life cycle analysis, the embodied energy should be included; the credit is electricity consumption.

2. METHDOLOGY

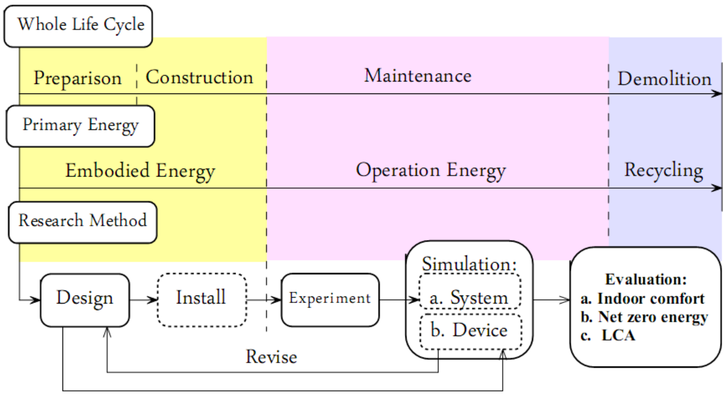


Figure 3. *Simulation appliances*

Table 1. *Typical life style*

Item	Parameter
NO. of occupants	3
Occupancy schedule (Workday)	0:00 AM-7:00 AM 7:00 PM-12:00PM
Occupancy schedule (Saturday)	0:00 AM-9:00 AM 5:00 PM-12:00PM
Occupancy schedule (Sunday)	0:00 AM-12:00 PM

As for possible applications of simulation, figure 3 is a data flow diagram to show the stages and research objects involved. The whole life cycle of ZEB can be divided into 4 stages, including: preparation (manufacture and transport), construction, maintenance and demolition. The primary energy needed during the whole life time includes: embodied energy, operation energy and recycling energy. Regarding the research works, design, experiment, simulation and evaluation are the main stages in which simulation tool is playing a more important role, as figure 3 shown. At the first stage, it can supply a load analysis as a guideline for the design of energy system. At the experiment stage, the test results can be predicted via simulation. At the same time, the simulation system can be updated as well based on the experiment verification. Finally, the performance data, which cannot be easily obtained through experiment under some external conditions, can be got based on the verified simulation results. A comprehensive analysis can be carried out based on the available data in terms of indoor comfort, energy balance and life cycle assessment (LCA). One should be note that the simulation is based on the typical Shanghai occupant’s life style in the residential building and the main information for this life style is shown in table 1. The weather data are from two typical meteorological year (TMY) files of data source: Chinese Standard Weather Data (CSWD) (China Meteorological Bureau and Tsinghua University, 2005) and Chinese Typical Year Weather (CTYW) (Zhang and Huang, 2008).

3. CASE STUDY

The case study is about a 93 m^2 zero energy apartment (ZEA) which is built on the third floor of a green building on the campus of Shanghai Jiao Tong University, as shown in figure 4(a). The whole building 3D model is shown in figure 5. The apartment with the high performance envelope is used as a test and demonstration platform for building energy efficiency technologies. The inside structure of apartment was designed and decorated according to the demand of a typical Chinese household, as illustrated in figure 4(b).

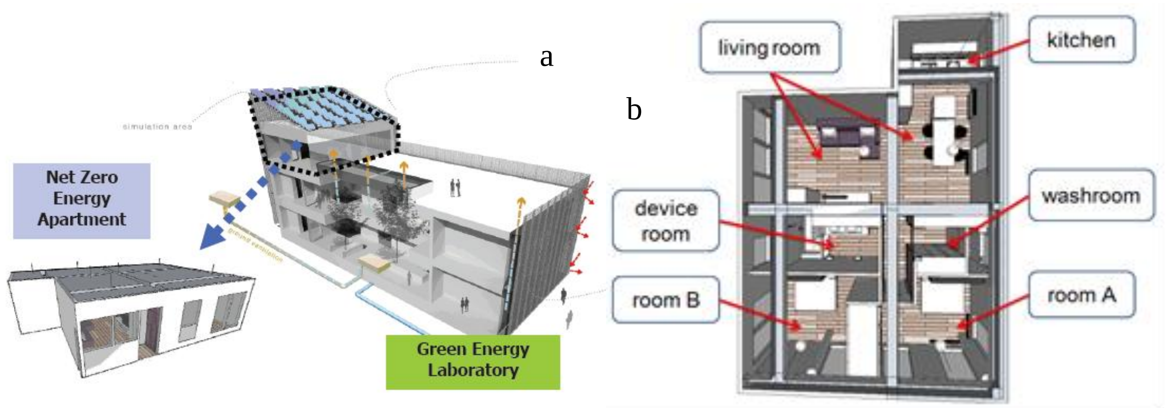


Figure 4. *Architectural design: (a) ZEA; (b) inside structure*

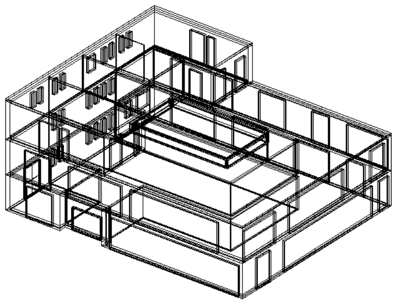


Figure 5. *3D model of main body*

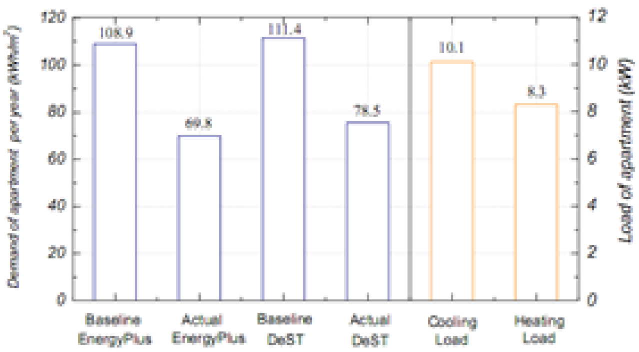


Figure 6. *ZEA load*

Based on the design information, the building load is predicted through simulation. Two pieces of simulation software are applied: EnergyPlus and DeST. The calculation result is compared with baseline building which is defined in local code (Ministry of Housing and Urban-Rural Development, 2001), as shown in figure 6. The results show that the cooling and heating load of the apartment are 10.1 kW and 8.3 kW, respectively. The annual energy demand of apartment is 69.8(kWh/a) from EnergyPlus, and 78.5(kWh/a) from DeST. It should be noted here that the load calculation is just for a comparison of passive design with the simplification model of an ideal energy system.

Based on the calculated load, the energy system was designed for ZEA. Figure 7 shows the design concept of energy system in the ZEA, concerning the relationship among sources, devices and end user. The solar energy is applied as a main renewable energy source for cooling and heating and also electricity generation. The main devices are a solar collector (SC) loop and a hybrid heat pump which integrates a small scale LiBr absorption chiller with a conventional CO_2 heat pump (HP) (see figure 8 and 10). The main demands for end-user are cooling, heating, DHW, appliance and lighting. One home energy management system (HEMS) will be employed for the entire system, after the enough data are collected from the individual test, experiment or debug of subsystems. On a sunny day of winter, solar energy can be delivered through solar collector loop to the end-user side for heating and DHW. On a cloud day, CO_2 heat pump will be operated independently without the assistance of solar energy. For a sunny day in summer, solar assisted cooling energy from the absorption chiller is input into the refrigeration loop of CO_2 HP in cooling mode, so that the maximum cooling load can be met. For a cloud day in summer, the cooling load decreases with the decline of solar radiation, CO_2 HP can independently operate in cooling mode to supply enough cooling capacity to the indoor space. And the electricity consumption of the entire system was offset by the photovoltaic (PV) arrays.

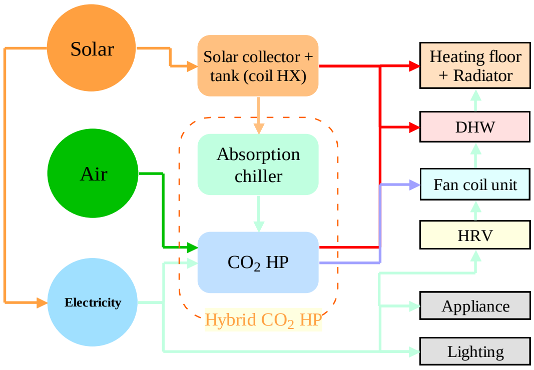


Figure 7. Design concept of energy system

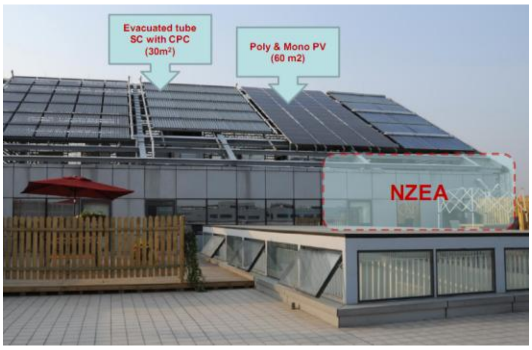


Figure 8. Photo of SC and PV

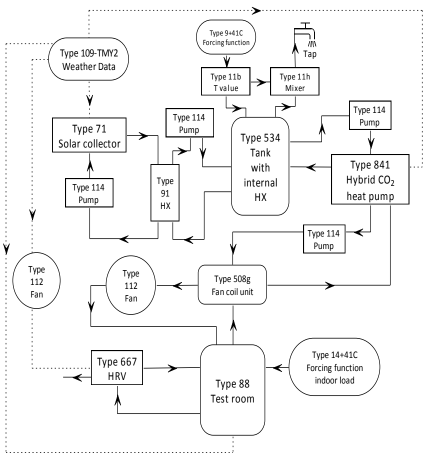
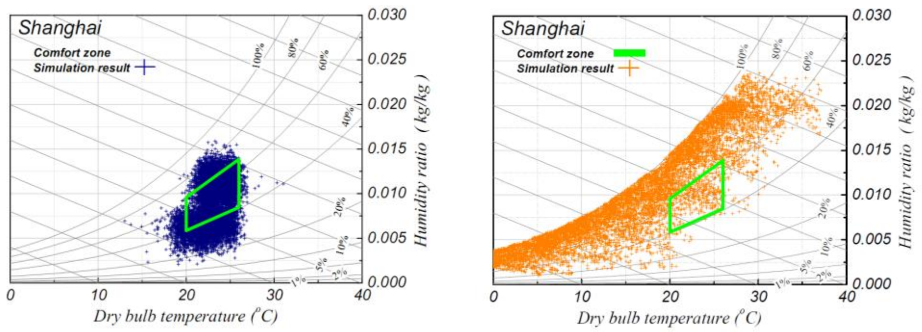


Figure 9. System layout in TRNSYS

Figure 10. Demonstration hybrid HP system

After design stage, the experiment system was installed. Some of experiment results in steady state can be fitted to performance curves or equations, such as data of SC, HP and PV. These parameters are used in the developed simulation module (see figure 9). Some other data in simulated system, such as parameters of pump, fan coil unit, are from catalogue data of manufacturer. The simulated results are verified through experiment data and the comparison results shows that the relative error can be limited below 13% (Deng, et al, 2010). With the annual system simulation, the hourly data of energy consumption, indoor temperature, etc. can be obtained for evaluation.

4. RESULTS



(a) Indoor environment (b) Outdoor environment

Figure 11. *Temperature and humidity ratio distribution for 8760 hours*

The result regarding the apartment indoor comfort from the system simulation is the first evaluation indicator. It can also be considered as the base of evaluation, because the energy-saving would lose its rationality if an accepted indoor comfortable level cannot be achieved. Figure 11 shows psychrometric diagrams of the simulated temperatures and humidity for the indoor environment of ZEA and ambient environment as well as a defined comfort zone (20-26 ℃ and 40-65% relative humidity). There are result points for occupancy hours (5204 hours) in every figure based on a whole year simulation. One indicator, namely comfortable zone fraction (CZF), which denotes how many result points are inside the comfortable zone are defined and calculated. By CZF, the influence from HVAC system on the comfortable level of indoor environment can be evaluated. Similarly, an indicator, namely, comfortable temperature fraction (CTF), is defined to show how many points are inside the comfortable temperature range (20-26 ℃). The CZF reaches 52.23% and CTF reaches 94.38%.

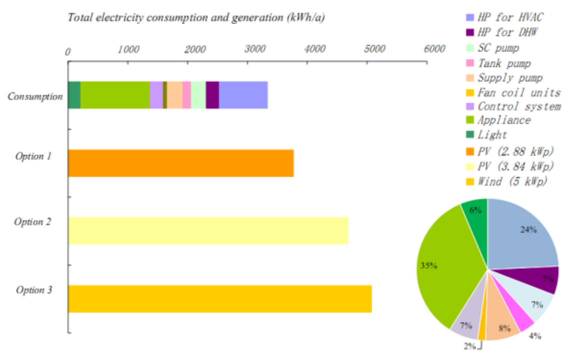


Figure 12. *Balance between consumption and generation, distribution of energy consumption*

Table 2. *Simulation result for different life styles*

Items Consumption	*Chinese* (kWh/m^2)	*Japanese* (kWh/m^2)	*American* (kWh/m^2)
HVAC	8.69	25.72	32.15
DHW	2.71	4.04	4.13
Control system	2.39	3.10	3.24
Appliance	12.44	14.71	41.76
Light	2.28	16.35	18.68
Total	33.49	63.92	99.96

PV Generation			
Lowest capacity for balance (kW)	2.4	4.5	6.9
Lowest area for PV installation (m^2)	20	38	58

The result for couple operation simulation between system and building is shown in table 2. The total electricity consumption for the typical Chinese life style is 33.49 kWh/(m^2a). The HVAC and DHW system, including HP, pumps and terminal units, takes 52% of total electricity consumption, as figure 12 shown. The percentage of electricity consumption in control system is round 7%. The other parts take approximately 41% of the total consumption. In summary, total electricity consumption for the Shanghai life style is 3335kWh for one year. Besides, 2.88kW PV, 3.84kW PV and 5kW wind turbine are used as three options of renewable energy power supply, according to the real experiment system. Based on the simulation, 2.88kW polycrystalline PV can output 3767kWh per year. In addition, the electricity generations of 3.84kW PV and 5kW wind turbine are 4681kWh and 5072kWh per year in Shanghai, respectively. Thus, three options regarding the renewable energy supply are proposed to offset the energy consumption of maintenance (or called operation), as shown in figure 12. The annual electricity consumption can be offset by the generation of option one which has the least cost and surplus 432kWh electricity generation can be available to shorten the recovery time of investment.

As per this evaluation method, the electricity consumption results for typical Japanese life style and American life style are calculated as well. The data regarding the average electricity consumption per household in these two countries are used as reference (Nakagami, 2006, Ariu, et al, 2011).The results show that the Japanese lifestyle consumes nearly two times electricity of Chinese life style and therefore need 4.5 kW PV at least to offset consumption. The main consumption parts for America life style are about HVAC&DHW and appliance and they take 32.16% and 41.78% of total values, respectively. The lowest PV power for net zero balance is 6.9 kW, which takes nearly 58 m^2.

CONCLUSION

Because passive design of building has already been a mature technology and can be realized in a near-fixed process by simulation software, energy system design for ZEB may become the other focus regarding how to further improve total performance of ZEB. Energy system of ZEB, such as HVAC and DHW system, could be more efficient with the assistance of renewable energy. New configurations and system integration are needed to promote the system become more compact and reliable. As for power generation system, on-site self-supply or distributed energy systems will be depended on the smart control so that renewable energy could be easily integrated with the central grid network via smart metres. The case study shows possible applications in the evaluation of ZEB. Base on the experiment and simulation results, analysis regarding the indoor comfort and energy balance. The results show that the total electricity consumption can be reduced to the amount of 33.49kWh/m^2 and it can be offset by a 24m^2 PV array. In addition to the achieved energy balance for the goal of net zero, the indoor temperature can meet the comfortable request during the 94.38% time for the whole year.

ACKNOWLEDGEMENTS

This work was supported by the Key project of the Natural Science Foundation of China under the contract No.50736004, and also the Key project of the Natural Science Foundation of China for international academic exchanges under the contract No.51020105010. The authors would like to express their gratitude to Italian Ministry for Environment, Land and Sea for their financial support to Green Energy Laboratory.

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