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Case Study of Net Zero Energy Apartment

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ABSTRACT

A case study regarding an apartment of net zero energy (NZEA) in Shanghai is introduced in this article. The passive design of energy efficient, solar collector system, HVAC&DHW system, indoor terminal units and renewable energy power system of the building are introduced briefly, particularly the concept of the energy system. Based on performance curves obtained from the experiment, a simulation model for the whole system is established for the evaluation. The performance of NZEA was evaluated in terms of the indoor comfort, energy balance and life cycle assessment.

1. INTRODUCTION

Commercial and residential buildings use almost 40% of the primary energy in the United States (Crawley et al., 2009) and Europe (Aste et al., 2011), and nearly 30% in China (Tsinghua University, 2008). A number of works are being done worldwide to reach the high performance goals in the building section and reduced the dependence of building section on the primary energy. Using an approaching goal of net zero energy building (NZEB), the related energy and environment problems will be addressed in an aggressive and integration way. Regarding the definition of a net zero energy building, USA department of energy (D.O.E) has present a comprehensive definition which covers four kinds of high performance buildings and their boundaries and metrics (Crawley et al., 2009). Furthermore, Satori et al (2012) discussed the criteria for definition of NZEB and REHVA Task Force (2011) proposes a technical definition for nearly zero energy buildings required in the implementation of the Energy performance of buildings directive recast. Hernandez and Kenny (2010) discussed the similarities and differences of various related definitions, and defined a life cycle zero energy building (LC-ZEB). Kilkis (2007) introduced a new metric for net zero carbon buildings (ZECB) and net zero exergy buildings (NZExB). The status and perspectives of low energy and net zero buildings in German was reviewed (Voss et al., 2011). Two anther review articles about the definition of zero energy buildings (ZEB) are present by Torcellini et al (2006) and Marzsel et al (2010). In addition to definition, boundary and metric, some technologies which can be integrated with NZEB are discussed in references (Aste et al., 2011, Satori et al., 2010, Kolokotsa et al., 2011, Kerr and Kosar, 2011), in the terms of roadmap and demonstration towards net zero energy.

Regarding the NZEB cases, a literature search suggests that most of projects summarized in the introduction section of former publication (Deng et al., 2010) are focused on a feasibility research or simulation evaluation. The case which covers the integration design, the real operation and the performance evaluation of NEZB are rare. In this article, a case study about a net zero energy apartment (NZEA) in Shanghai is present. The features of passive design, building service system, renewable energy power system are introduced briefly. The experiment and simulation of key components in the system, such as solar collector, hybrid CO_2 HP and photovoltaic panel, are not introduced in this article owing to the space constraint, but can be found in the other publications of authors. Based on the experiment and simulation, the performance of NZEA was evaluated in terms of indoor comfortable, primary energy payback time and CO_2 emissions equivalent savings.

2. PROJECT DESCRIPTION

The research object is a 90 m^2 apartment which is built on the third floor of a green building on the campus of Shanghai Jiao Tong University, as shown in Figure 1(a). The apartment with the high performance envelopment 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 1(b).

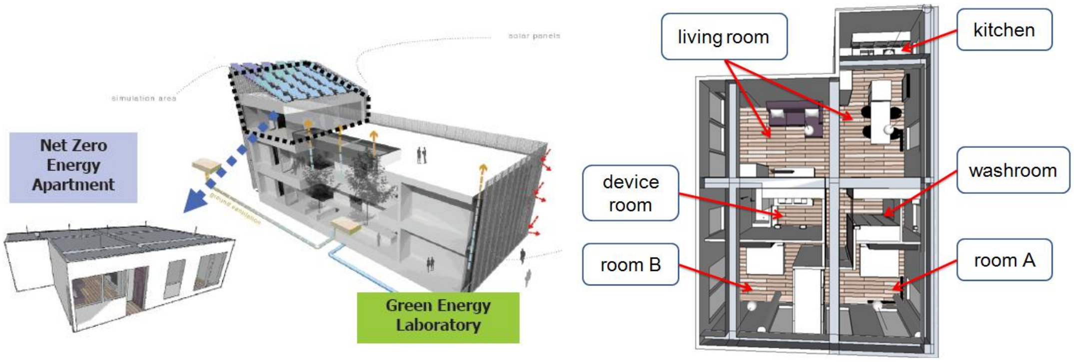


Figure 1: Architectural design: (a) NZEA (b) inside structure

2.1 Passive design

Figure 2 shows the mean values of ambient temperature, relatively humidity (RH) and daily solar radiation for twelve months. The data are from two typical meteorological year (TMY) files of data source: Chinese Typical Year Weather (CTYW) (Zhang and Huang, 2008) and International Weather for Energy Calculations (IWEC) (ASHRAE, 2001). The highest temperature in summer nearly reaches 30^{o}C and the lowest in winter is around 5^{o}C. The relativity humidity (RH) keeps at a high level (above 65%) during the whole year and almost reaches 80% in summer. The solar radiation results proved the utilization potential is good enough for DHW through the conventional solar collector (SC). However, if the solar thermal is intended to drive an absorption chiller, the high performance solar collector is necessary. In a summary, the feature of local weather conditions is "hot summer and cold winter". According to these weather conditions and China code <<Design standard for energy efficiency of residential buildings in hot summer and cold winter zone (JGJ 134-2001)>> (Ministry of Housing and Urban-Rural Development, 2001), the thermal insulation performance of envelopment is designed. The result, which is stricter than the request of the code, is listed in Table 1.

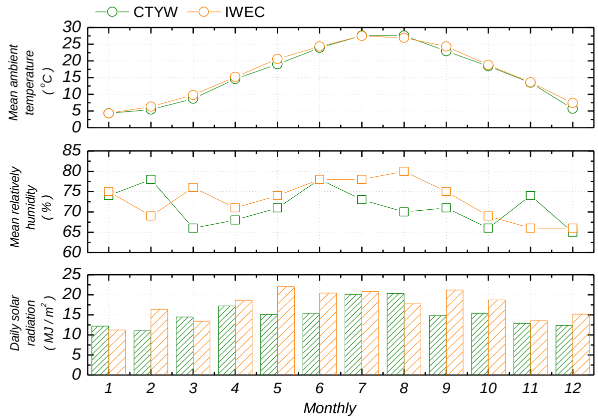


Figure 2: Weather conditions of Shanghai

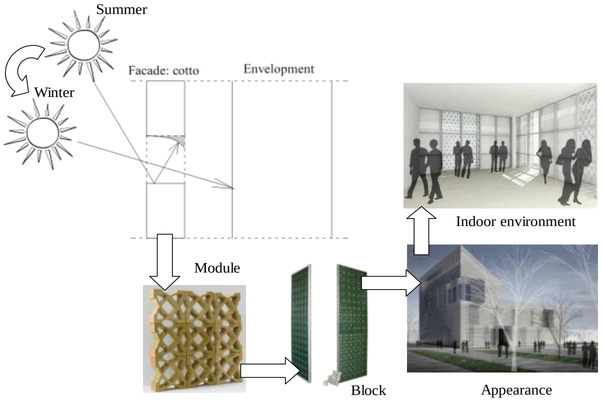


Figure 3: Facade of apartment

In addition to the design regarding the thermal insulation of envelopment, an outside facade for increasing the shading coefficient of inside glass-curtain wall was also considered in the design. The final design employs "cotto" facade, which has no movement components, and is recyclable material of clay. The rendering pictures of appearance and visual effect of the inside environment are shown in Figure 3.

Based on the passive design, the building load is calculated through simulation. Two simulation software are applied:

EnergyPlus and DeST. The calculation result is compared with baseline building performance, as shown in Figure 4. The results show that the cooling and heating load of 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.

Table 1: Passive design parameters of NZEA

NZEA	Surface [m^2]	U value [W/(m^2K)]	G value [-]
Floor	93	0.30	-
Facade. S	45.9	0.31	-
Facade. N	45.9	0.31	-
Facade. E	32.6	0.31	-
Facade. W	32.6	0.31	-
Roof	93	0.21	-
Window. S	7.92	2.5	0.62
Window. N	10.32	2.5	0.62
Window. E	6.96	2.5	0.62
Window. W	0	-	-
Other features		two skins facade	

2.2 Energy System

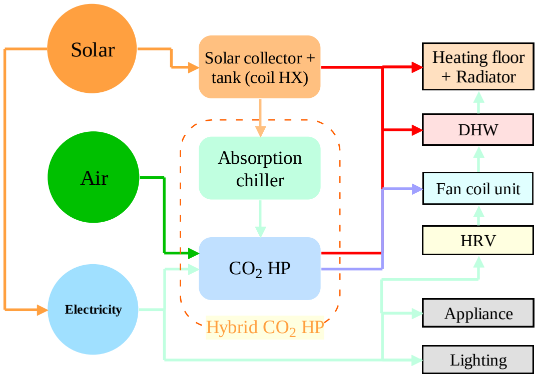


Figure 5: Design concept of energy system

The energy system here means the entire building service system for the apartment, including solar collector system, HVAC&DHW system, indoor terminal units and renewable energy power system. Figure 5 shows the design concept of energy system in this NZEA, concerning the relationship among sources, devices and end user. The solar energy is applied as a main renewable energy source to supply cooling and heating and to electricity generation. The devices contain a solar collector system and a hybrid CO_2 heat pump which will be introduced in the following. 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.

2.2.1 Solar collector (SC) system: The SC array is installed on the slope steel frame above the roof of apartment as shown in Figure 6. The applied SC is a type of evacuated glass tube (EGT) collector with CPC reflector. Its configuration is shown in Figure 7. In addition to the innovation in the selective absorption coating, the CPC reflector is another main updating for the conventional EGT SC. It can obviously increase radiation absorption area of SC without tracing system, so that a higher efficiency can be achieved. The performance comparison with a black hose and a flat plate SC is also shown in this figure. It can be seen that the efficiency of EGT collector is obviously higher than that of flat plate type when the application aim is a production of high temperature water (34.5^{o}C plot line). And for solar-thermal-driven air-conditioning (65.5^{o}C plot line), the CPC EGT collector can act as a reasonable thermal source for cooling in summer and heating in winter, with less electricity consumption.

2.2.2 HVAC&DHW system: An 8kW air-cooled hybrid carbon dioxide (CO_2) heat pump (HP) which uses the solar thermal energy to assist a electricity-driven vapor compression (VC) air conditioning is developed. The main components of this device are a small solar thermal-driven Libr absorption chiller and a CO_2 HP. The assisted cooling is mainly used for the further cooling of CO_2, when CO_2 leaves the air-cooled gas cooler. This technology solution can dramatically decrease the outlet temperature of CO_2 which leaves the gas cooler by heat exchange with the chilled water of high temperature (15-18^{o}C) from the absorption chiller. In this case, the proper extra-cooling capacity can be created and a higher COP can be achieved. It also means that electricity consumption of the entire device can be reduced by the solar energy input. In summer, the solar thermal energy is collected by solar water collectors. The thermal energy is then transferred from a storage tank (500L) to the loops of HP and DHW. The Hybrid CO_2 HP supplies chilled water to the fan coil unit. In winter, the solar thermal energy can be directly supplied to the radiation floor (70m^2) or radiator. If water temperature of collector tank is not high enough, the CO_2 heat pump is operated as a backup.

Figure 6: Photo of solar collector array and PV

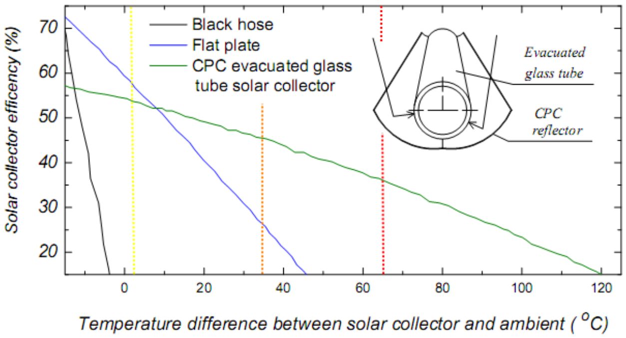


Figure7: Performance comparison of solar collector

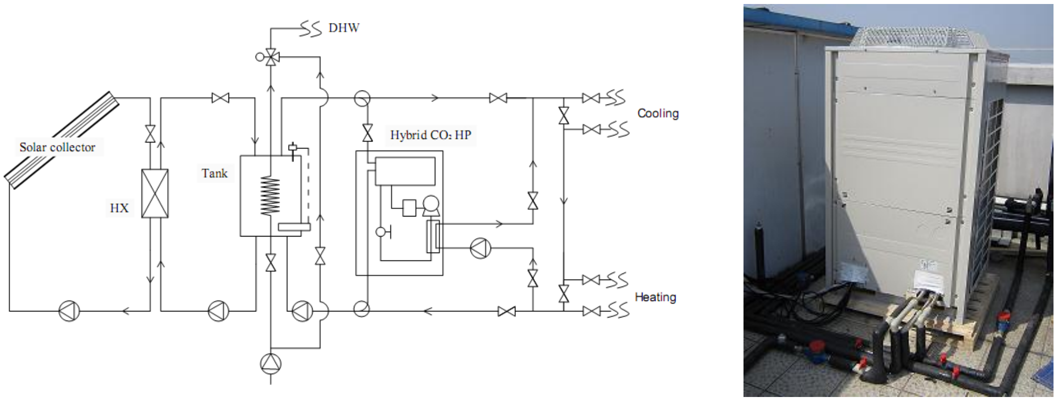


Figure 8: HVAC&DHW system: (a) layout of pipe system (Simplified version in cooling mode); (b) Hybrid HP unit

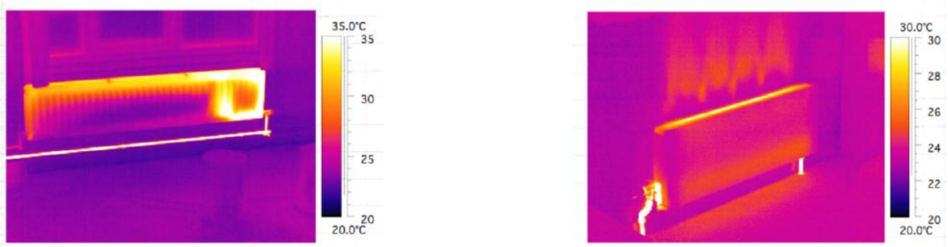
2.2.3 Indoor terminal unit: One 127W heat recovery ventilator (HRV) is used for recovering the both latent and sensible heat from the exhaust air. In addition, 70 m^2 heating radiant floor was installed for a comparison test with innovation fan coil units and radiators. There are various types of terminal units tested in the demonstration apartment. Some typical types are shown in Figure 9. In order to obtain an even distribution and quick response of heat release, boost fans and control system are added into a conventional design of radiators to form a new design. The infrared pictures of Figure 9 show a compare result after the operation starts 270 seconds between a conventional steel radiator and this innovation design. The temperature of the conventional radiator continues to rise at the flow end and across the head; however the part of return flow is still cold. There exists obvious uneven temperature distribution and overheating. The surrounding environment can not be warmed up quickly from the startup of system. On the contrary, the effect of radiative is improved in the case of innovation radiator, in terms of temperature distribution, response speed and interaction with environment. This design is well suit for the typical life style of Chinese households who are custom to shut down the HVAC system during the unoccupied time.

Furthermore, the innovation radiator also has some advantage in water-saving and material saving, as listed in Table 2.

2.2.4 Renewable energy power system: Renewable energy power system, which is installed for the entire building, consists of two photovoltaic (PV) arrays (60m^2, see Figure 6), a 5kW wind power system, inverters, controllers and meters for export and import. The outputs of polycrystalline and monocrystalline arrays are 2.88kW and 3.84kW, respectively. Table 3 shows the main parameters of polycrystalline PV and wind turbine. When the electricity generation from renewable energy power system is not enough for consumption, the grid will output the power to the office zone and demonstration apartment in the building. Thus, the apartment can benefit from a reliable power supply by using this off-grid power generating system. Figure 10 presents a schematic diagram of the power system. The whole power system is used to check whether the energy consumption of the entire building service system can be offset by the renewable energy generation. It should be noted that the wind turbine system is used as a backup power system, not only for demonstration apartment, but also for the other zones in the laboratory building. Thus, its electricity generation is only used as one comparison case in simulation and it not contained in the final evaluation of affordable NZEA.

Under floor fan coil unit

Radiator with boost fan



Infrared pictures of conventional radiator

Infrared pictures of innovation radiator

Figure 9: Photos of indoor terminal units

Table 2: Parameter comparison among different radiators.

Item	Cast iron radiator	Traditional radiator	Low-H_2O radiator
Water content (L)	25	7	1
Weight (kg)	105	37	4
Material	Steel	Steel	Copper/aluminum
Warm-up rate	Very slow	Slow	Fast

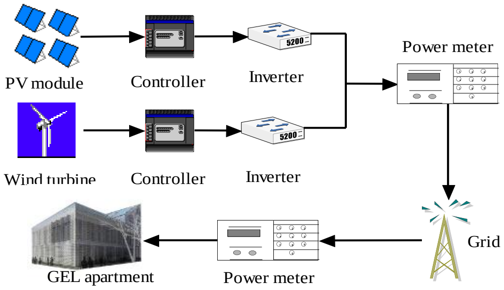


Figure 10: Design concept of renewable energy power system

3. EVALUATION

In order to evaluate the performance of apartment, the indoor comfort level was firstly analysis based on the simulation results. Further, the primary energy payback time is calculated for the apartment, because it can be considered as a “net zero energy” evaluation for the whole building life cycle. Based on this comprehensive evaluation, the CO_2 equivalent saving can be also obtained.

Regarding the methodology of evaluation, Figure 11 is a data flow diagram to show the scope and object used in the evaluation as well as tools and indexes. The whole life cycle of NZEA can be divided into 4 processes, 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 method, design, experiment, simulation and evaluation are the main approaches. The design results are validated by the devices simulation, and performance of device unit can be predicted. The erection can realize the design idea. After that, performance parameters and curves of components in the entire system can be obtained through various steady state experiments. The performance information is then input into a system simulation module so that the system performance of a hourly dynamic operation can be recorded for evaluation. The evaluation indexes in this article are the indoor comfort, energy balance for net zero energy and impact of energy and environment during the life cycle.

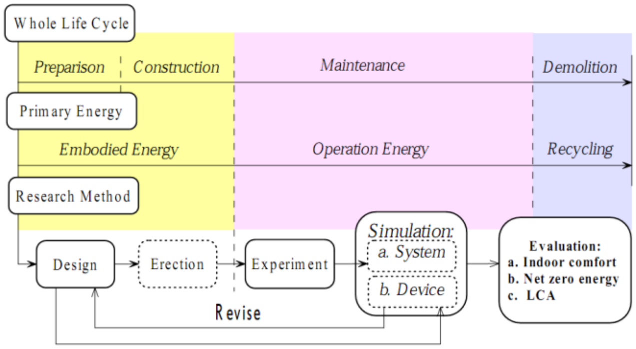


Figure 11: Flow diagram of evaluation

3.1 Indoor Comfort Evaluation

The result regarding the apartment indoor comfort from the system simulation is the first evaluation index. And 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 12 shows psychrometric diagrams of the simulated temperatures and humidity for the indoor environment of NZEA and ambient environment as well as a defined comfort zone (20-26 ℃ and 40-65% relative humidity). There are result points for 8760 hours in every figure based on a whole year hourly simulation. One parameter, 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 index, namely, comfortable temperature fraction (CTF), is defined to show how many points are inside the comfortable temperature range (20-26 ℃). The simulation results for these two parameters are both shown in Table 4. The CZF reaches 45.83% and CTF reaches 92.67%.

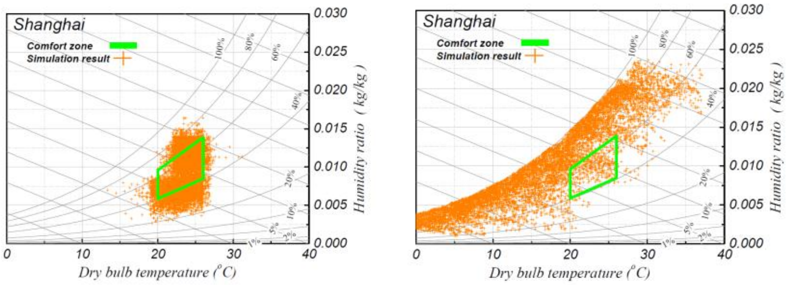


Figure 12: Temperature and humidity ratio distribution for 8760 hours: (a) Indoor environment; (b) Outdoor environment

3.2 Net Zero Energy Analysis

The result for couple operation simulation between system and building is shown in Table 4 as well as one reference case installed in Madrid (Deng et al., 2010). The total electricity consumption for the typical Chinese life style is 84.22 kWh/(m^2a). The HVAC and DHW system, including HP, pumps and terminal units, takes 59.39% of total electricity consumption, as Figure 13 shown. In GEL, the backup heat source is HP, not the assisted electricity heater. Thus, the electricity consumption for this part is smaller than that of NZEB in reference (Deng et al., 2010). The percentage of electricity consumption in control system is round 8%. The other parts take approximately one third of the total consumption. In summary, total electricity consumption for the Chinese life style is 7832kWh for one year. Besides, 2.88kW PV, 3.84kW PV and 5kW wind turbine are used as three schemes of renewable energy power supplies, 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 5072kWh and 4681kWh per year in Shanghai, respectively. Thus, three cases regarding the renewable energy supply are proposed to offset the energy consumption of maintenance (or called operation), as shown in Figure 13. The energy solution of first case is a combination of two PV arrays (6.72kW). The total electricity generation is 8839kWh per year. The annual electricity consumption can be offset by the generation of this solution and surplus 1007kWh electricity generation can be available to shorten the recovery time of investment.

Table 4: Simulation result of system

Item	GEL	Reference case
Consumption		
HP	25.05	13.5
SC pump	7.8	7.7
Tank pump	4.06	
Supply pump	8.42	
Fan coil units	0.65	0.6
DHW	4.04 (Assisted HP)	3.20 (Assisted electricity heater)
Control box	6.72	23.5
Appliance	11.13	23.5
Light	16.35	
Inverter	-- *	2
Total	84.22	74
Generation		
PV (2.88 kW_p)	40.50	203.80（12.5 kWp）
PV (3.84 kW_p)	54.54	
Wind (5 kW_p, backup)	50.34	--
Indoor comfort		
Comfortable temperature fraction (%)	92.67%	99.37%
Comfortable zone fraction (%)	45.83%	46.76%

* The electricity consumption of inverter is not shown in the table, because the power generation shown is already the final generation after inverter.

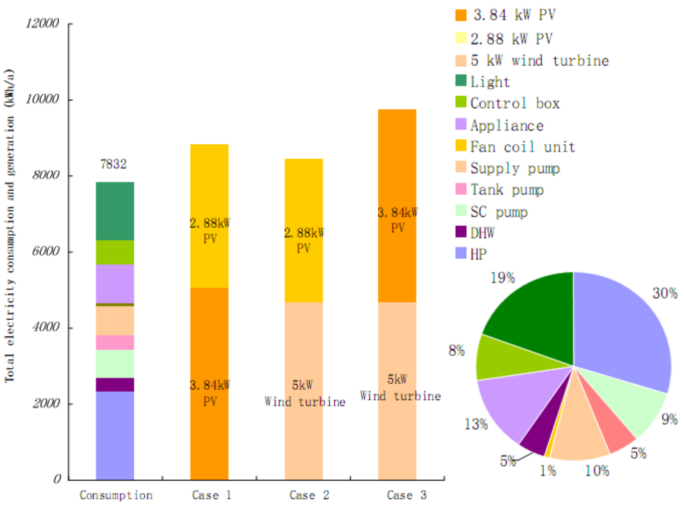
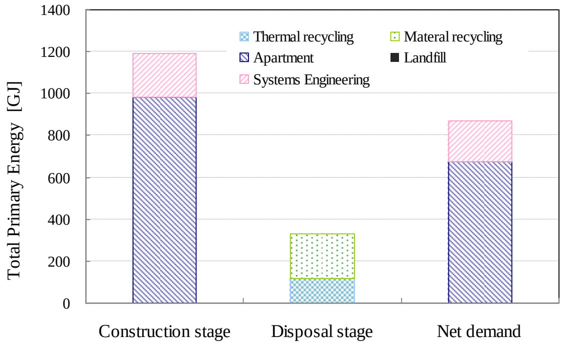


Figure 13: Balance between consumption and generation, distribution of energy consumption

3.3 Life Cycle Assessment

Objects of the assessment is limited into the apartment and system during the whole life when is from the construction, operation to the end of apartment life. The total fossil primary energy necessary for materials and system has been calculated and estimated to 868GJ through inventory analysis. At the end of life, those materials can be either recycled, or incinerated (thermally used), or put in landfills. The effective total primary energy needed for the apartment material is then 676GJ. The total embodied energy over the life cycle, as well as the recycling potential, is illustrated in Figure 14. The total energy needed for operation and energy generation from renewable power system has been shown in Figure 13.

Figure 15 shows breakdown of the primary energy demand for construction materials. The “other parts” in this figure, which contains seal, mineral wool, gluten, polyolefin film, etc., takes 27.9% for total primary energy. Insulation glass takes the second highest percentage, because the window-wall ratio of the south facade is around 70.0%. The steel part accounts for 15.1%, because all the building body is a steel frame type.



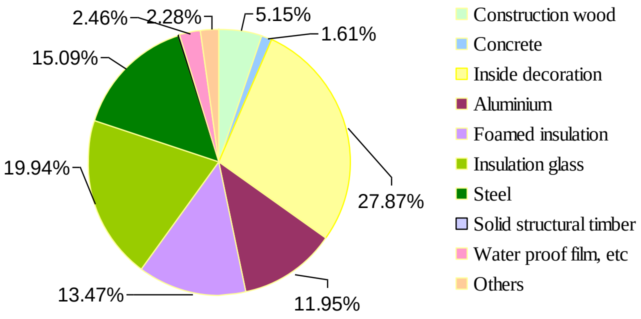


Figure 14: Embodied and recycling energy **Figure 15:** Breakdown of primary energy demand for materials

Based on this calculation result for construction and the simulated energy demand during operation, the primary energy payback time (N_{PE}) can be calculated. Primary energy factors (PEF) for the conversion from electricity to fossil primary energy are needed for this calculation. The conversion factors of GEMIS (a life-cycle assessment program and database for energy, material, and transport systems) have been used to consider the electricity mix generation of China (GEMIS, 2010). The calculation equation can be seen in Equation (1). It can be found that N_{PE} is highly depended on the installed capacity of renewable energy, when the primary energy demands of construction and maintain are fixed as well as convention factor. With the increase of PV capacity, the N_{PE} decrease, as table 4 shown. If the PV capacity can be increased to 10kW, the payback time can be limited below 10 years. Once the primary energy needed has been recovered, the CO_2 equivalent emissions savings during the rest of the lifetime can be estimated, as Equation (2) shown. The conversion factor of GEMIS for China electricity mix is used and the value is 0.813kg/kWh$_{el}$. One other conversion factor from one China research result (Wang and Feng, 2006) is also used as a reference and the value is 0.921 kg/kWh$_{el}$. The lifetime of apartment is assumed as 50 years. The results show that CO_2 equivalent savings are 173.05T and 196.04T (SI: T, or ton), respectively, for GEMIS and MOST conversion factors.

$$N_{PE} = \frac{Q_{construction}}{(Q_{renewable} - Q_{maintain}) \times PEF} \tag{1}$$

$$M_{total} = F_{CO_2} \times (Q_{renewable} - Q_{maintain}) \times (N_{LT} - N_{PE}) \tag{2}$$

Table 5: CO_2 emissions equivalent savings for NZEA in 50 years of building life

Item		N_{PE} (Year)	CO_{2eq} emissions saving (T or ton) GEMIS	MOST
Proposal PV capacity	7 (kW)	39	12.30	13.93
	8 (kW)	20	65.62	74.34
	9 (kW)	13	120.50	136.51
	10 (kW)	10	173.05	196.04

4. SUMMARY

In this article, a case study regarding NZEA is introduced in terms of design and evaluation. Based on the performance data of experiments, the numeral model was built and system simulation can be carried out to obtain the electricity consumption and indoor comfortable parameters for the whole year. And these results can be used for the evaluation of NZEA, analysis regarding the indoor comfort, energy balance and environment impact was performed as well as a life cycle assessment.

With respect to the design of NZEA, solar energy is an important consideration for renewable energy input in this case. The first integration solution is the optimal absorption of solar radiation through the building elevation or the second skin facade. The fixed facade without movable elements is preferred because of no-energy-driven and low cost, but a deep design regarding the optic optimization, thermal ventilation between facade and elevation is necessary. The second integration solution is the solar thermal driven cooling and heating system, including solar air-conditioning, domestic hot water system, and combined heating supply system. Because of the intermittent supply and high cost, the independent solar HVAC and DHW system still keep at a demonstration stage, even though all the products are all available in market. The third solution is the PV array that is widely used in the existed NZEB projects. Due to limited surface area of building body and pollution of production process, existed silicon-based PV technology limited further development of NZEB and meets a challenge of technology update.

NOMENCLATURE

CPC	compound parabolic collector	(–)
DHW	domestic hot water	(–)
EGT	evacuated glass tube	(–)
F	conversion factor	(–)
M	CO_{2eq} emissions saving	(T/ton)
N	number of year	(year)
Q	primary energy	(GJ)
PEF	primary energy factors	(–)
SC	solar collector	(–)

Subscripts

el	electricity
eq	equivalent
LT	life time
PE	primary energy

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