Published in: Proceedings of the SET2010 - 9th International Conference on Sustainable Energy Technologies; Shanghai, China. 24-27 August 2010.

Energy supply concepts for zero energy residential buildings in humid and dry climate

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ABSTRACT: Energy supply concepts for zero energy residential building (ZERB) in Shanghai (humid) and Madrid (dry) are discussed in this paper. Simulation (TRNSYS) is employed as the main research method. Two typical housing models are designed according to the real occupancy condition of two cities as well as life schedule, thermostats settings, etc. An energy analysis considering the annual balance of input from the grid and output from renewable power systems is provided for the ZERB. Indoor comfortable comparisons between two cities are also presented to show optimal design strategies for HVAC under different weather conditions. Primary energy payback time and CO_2 emission reduction are presented to evaluate the performance of novel energy systems to show feasibility.

Keywords: zero energy building, solar energy, simulation

NOMENCLATURE

Q_{house}	total fossil primary energy needed for house construction (J)
Q_{PV}	annual PV electricity production (J)
Q_{cons}	annual electricity consumption (J)

1. INTRODUCTION

Nowadays, net zero energy building (NZEB) has already been recognized not only as an effective technical method to deal with energy shortage and environmental pollution all around the world, but also as an innovatory trend of design concepts in related research fields spanning building construction, HVAC, refrigeration and environment. Some research results of NZEB in recent years are summarized in the Tab. I. But most of the NZEB design has some shortcomings and limitations as below: (1) Less innovations in energy supply system. Actually energy supply system, especially HVAC and DHW system, takes a high proportion in the whole energy consumption of building. Significant energy saving can be achieved by the deliberate design in this part. (2) Lack of comparison. The design experience can not be easily shared because of local characteristic, such as: climate or life custom. (3) Cost. Most of the demonstration project paid more focus on the feasibility in net zero energy, not on the economical analysis. In this paper, two innovative energy supply systems are introduced based on the zero energy residential building (ZERB) design experience in Shanghai and Madrid. Two cities have their own special weather condition, the annual humidity level of Shanghai is higher but in Madrid, dry weather dominates. Some comparison results from simulation are given so that the energy system design schemes and primary energy payback time can be summarized under typical humidity/dry climate.

Table I: Literature summary in recent years [1-6]

Year	Authors	Location	Area (m^2)	Renewable energy	Feature	Method
2006	P.Norton et al	Denver, USA	120	4 kWp PV	$9m^2$ solar collector	Simulation Test
2006	A.Biaou	Montreal, CAN	156	$85.4m^2$ PV	8.75kW GSHP, HP assisted DHW	Simulation
2007	J.Steinbock et al	Minesota, USA	88.8	135.3 m^2 PV	GSHP, heat pump assisted DHW, total ventilation energy recovery	Simulation Test
2008	O.Siddiqui et al	Toronto, CAN	210	6.6 MWh/yr PV	GSHP, solar DHW	Simulation
2009	L.Wang et al	Cardiff, UK	--	1.32 kWp PV, 5kW wind turbine	GSHP, solar DHW	Simulation
2010	Y. Higuchi et al	Tokyo, JPN	106	34 m^2 PV	Heat pump DHW or solar DHW	Simulation

2. DESCRIPTION OF TWO ZERB CASES

The first case of ZERB is a test apartment which will be built on the third floor of a green building in the campus of Shanghai Jiao Tong University [7]. Its indoor structure was designed according to China typical apartment for 2 adults and 1kid household. The second ZERB case was planned and built by the Stuttgart University of Applied Sciences for the 1st edition of the Solar Decathlon Europe (SDE) that takes place in June 2010 in Madrid (Spain) [8,9]. The rendering design picture and passive design factors of two buildings can be seen in Fig.1, Fig.2 and Tab. II.

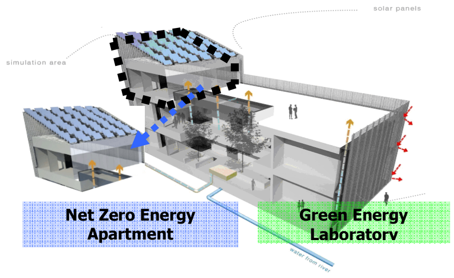

Figure 1: Concept design of the building 1

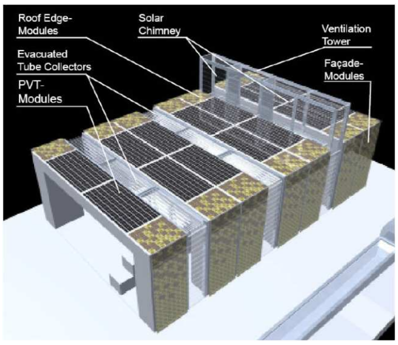

Figure 2: Computer rendering of building 2

Table II: Passive design of two buildings

	Building 1 (designed for Shanghai)			Building 2 (designed for Madrid)		
	Surface [m²]	U value [W/(m²K)]	G value [-]	Surface [m²]	U value [W/(m²K)]	G value [-]
Floor	93	0.30	-	56	0.1	-
Faç. S	45.9	0.31	-	16.6	0.13	-
Faç. N	45.9	0.31	-	16.6	0.13	-
Faç. E	32.6	0.31	-	22.8	0.16	-
Faç. W	32.6	0.31	-	22.8	0.16	-
Roof	93	0.21	-	56	0.11	-
Win. S	7.92	2.5	0.62	12.7	0.52	0.58
Win. N	10.32	2.5	0.62	12.7	0.4	0.4
Win. E	6.96	2.5	0.62	4.4	0.52	0.58
Win. W	-	-	-	4.4	0.52	0.58
Win. R	-	-	-	6.8	0.52	0.58
Feature	two skins facade, slope overhead PV roof, nature ventilation in interlayer and overhead space			module design, passive cooling, solar chimney, natural ventilation, night radiative cooling with PVT modules,		

3. ENERGY CONCEPT

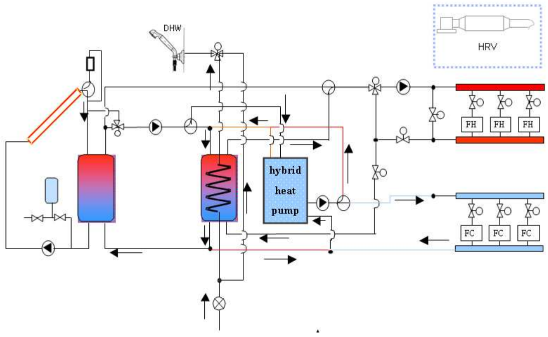

Figure 3: Layout of HVAC system

An 8 kW air-cooled hybrid heat pump (HP) which uses solar thermal energy to assist electricity driven vapour compression (VC) air conditioning device is developed for building one. The main parts of this device are a small solar assisted hybrid Libr absorption chiller and a CO_2 heat pump. Use of solar thermal driven Libr absorption cooling can dramatically decrease the outlet temperature of CO_2 when it leaves the gas cooler so that proper extra-cooling can be created. In this case, the hybrid heat pump can get a higher COP. It also means that electricity consumption of device can be reduced to a low level by solar energy input. In summer, the solar thermal energy is collected by 30m^2 heat pipe evacuated tube solar water collectors. Then the hot water is transferred from the collect tank (500L) into the storage tank (300L) to promote the performance of HP and supply thermal to DHW. Hybrid heat pump supplies cooling energy to the fan coil unit. In winter, the solar thermal energy can be directly supplied to the radiation floor (70m^2). If water temperature of collector tank is not high enough, the hp is operated to supply heating energy to storage tank. Then the thermal energy can be transferred to the indoor HVAC terminal units. When in the cloudy or rainy day, the hybrid heat pump works in independent operation mode. One 127 W heat recovery ventilator (HRV) is used for recovering the both latent and sensible heat from the exhaust air. The heating radiant floor and fan coil unit is used as terminal indoor unit. 64m^2 PV was designed for this apartment and it is located on the slope surface of overhead holder above the roof.

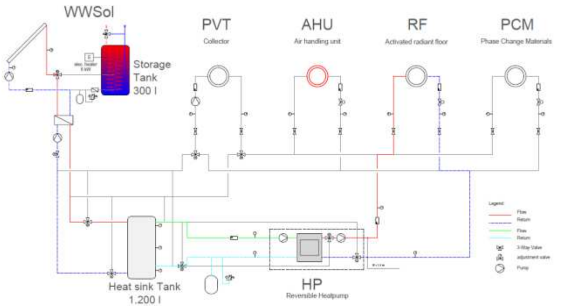

Figure 4: Hydraulic scheme of the system

The basic idea of the design is to use the traditional means for dealing with the hot and arid climate and to combine them with new technologies. Thermal mass (PCM), sun shadings and evaporative cooling will help to achieve a comfortable indoor climate with passive means. The ventilation tower supplies passively part of the ventilation and cooling needs by evaporative cooling using the wind as driving force. Mechanical ventilation (AHU) with heat recovery and indirect evaporative cooling systems is used to reduce heat losses in winter and provide additional cooling in summer. Active cooling and heating is supplied through a radiant floor (30 m^2) by a reversible heat pump (2.4 kW cooling) powered by photovoltaic (12.5 kW$_p$). In summer, a night radiant cooling system using hybrid PVT collectors (38 m^2) regenerates the PCM ceiling (18 m^2) and takes up the heat rejected from the reversible heat pump by cooling down the “heat sink tank”. If possible, “free cooling” is used by pumping directly the cold water of the heat sink tank to the radiant floor. Dehumidification of the supply air can be done with the reversible heat pump through a fan coil by cooling the air below the dew point. Domestic hot water (DHW) needs are covered by vacuum tubes collectors (6.6 m^2) which feed a 300 litre solar tank with electrical heater back-up. In winter, when necessary, the solar thermal system provides heat to the heat sink tank in order to increase the heat pump efficiency, as figure 2 shown. The PV system consists of around 66 m^2 of polycrystalline surface on both east/west facades and the roof and 33 m^2 of monocrystalline cells for the PVT modules.

4. WEATHER DATA

Both hot/dry and hot/humid climates from Madrid and Shanghai are considered in the simulation studies. The weather data used for the simulation studies are taken from Meteonorm[10]. Fig.5 shows that the mean ambient temperature of Shanghai is higher than that of Madrid in summer and there is a contrary trend in winter. The most obvious difference in weather between two cities is humidity for whole year. The mean relative humidity in summer of Shanghai is above 30% and keeps at a highest level for whole year. On the contrary, the lowest value of mean relative humidity in Madrid is less than 15% in July. The dry climate dominates the summer of Madrid. Fig.6 shows global horizontal irradiation of two cities for whole year. The average level of Madrid is better than that of Shanghai, especially in summer.

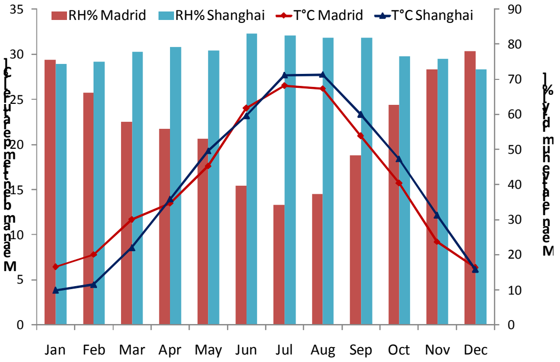

Figure 5: Mean ambient temperature and relative humidity comparison between Madrid and Shanghai

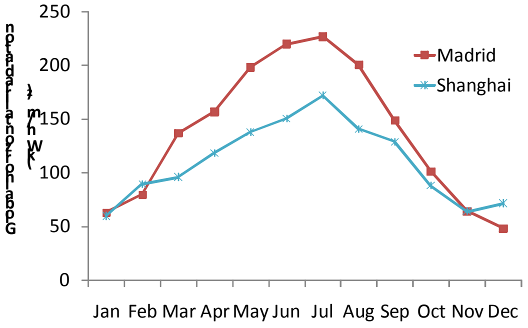

Figure 6: Global horizontal irradiation comparison between Madrid and Shanghai

5. INTERNAL GAINS

One weekly user profile is designed for every case, as Fig.7 and Fig.8 shown. The thermal indoor load profile of building 1 is based on the life custom of typical household (two adults and one kid). Daily DHW consumption is 80L/person. The thermal and humidity gain profile of building 2 is based on the building occupancy (2 people) and the electrical appliances of the house. Daily DHW demand corresponds to 50 litres/person with a 45°C set point temperature.

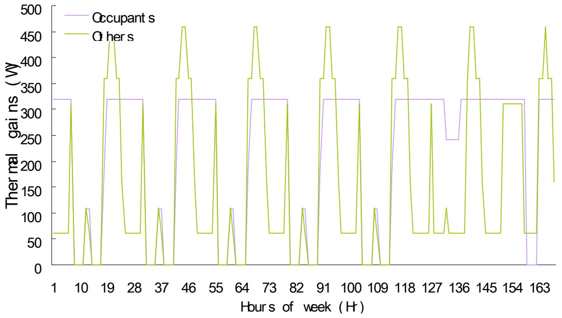

Figure 7: Thermal gains of building1

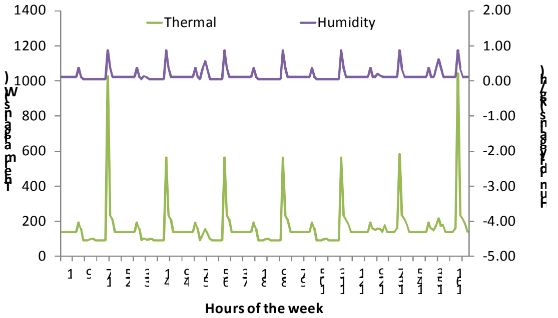

Figure 8: Thermal and humidity gains of building 2

6. SIMULATION RESULTS

Two detailed models about the house and their equipments for different cases have been implemented in TRNSYS [11] and the yearly simulations have been performed using the time step for 6 min. The simulation of the PV system for the building 2 has been done separately with INSEL [12]. For comparison, weather data files of two cities are input in the models. The main results are shown in table III.

Table III: Simulation main results

	Building 1		Building 2	
	Shanghai	Madrid	Madrid	Shanghai
Heating load (kWh/m^{2}a)	16.8	12.6	4.9	8.9
Cooling load (kWh/m^{2}a)	53.0	42.3	38.9	41.9
DHW load (kWh/m^{2}a)	41.0	43.1	30.3	29.8
Electricity consumption (kWh/m^{2}a)	89.5	85.7	68.4	75.1
Electricity production (kWh/m^{2}a)	94.1	119.6	203.8	152.0

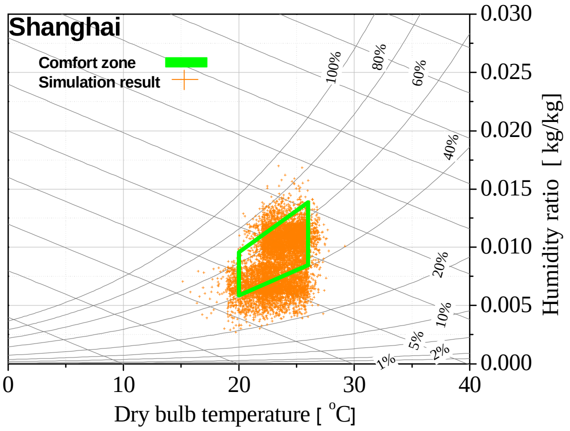

Figure 9: Building 1 result (Shanghai)

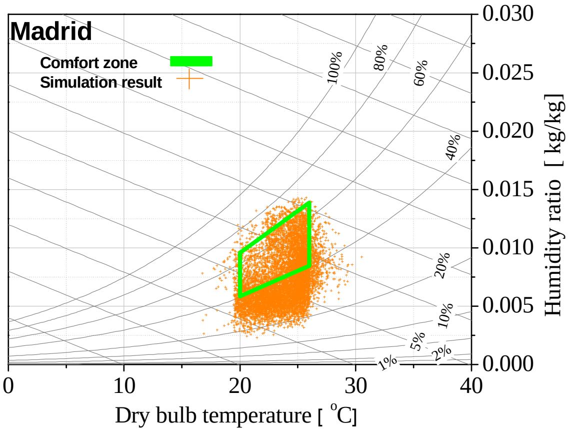

Figure 10: Building 1 result (Madrid)

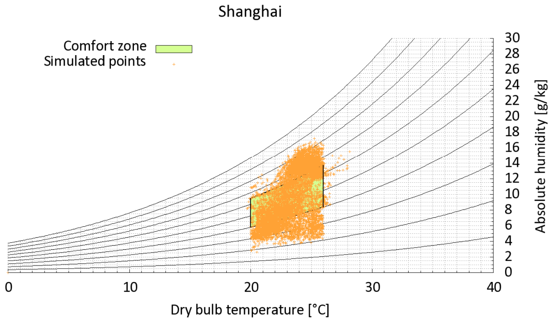

Figure 11: Building 2 result (Shanghai)

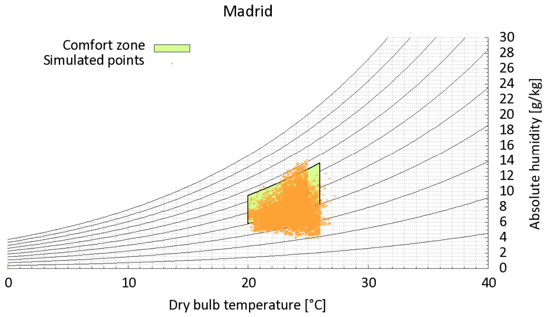

Figure 12: Building 2 result (Madrid)

Fig.9-12 show the psychrometric diagrams of the simulated temperatures and humidity for both climate conditions as well as the defined comfort zone (20-26°C and 40-65% relative humidity).

7. RESULT DISCUSSION

The energy consumption of building 2 is smaller than building 1, not only because the better passive design (lower G value in window, etc.), but also because of novel active cooling technology, such as, radiant floor "free cooling". The passive design features, such as, PCM ceiling and good thermal insulation, etc., make the hourly distribution of simulation results in building 2 more concentrated in the comfortable zone than that of building 1. The electricity balance is positive for both climates in both cases, although it is less favourable in Shanghai since the electricity consumption is higher and the PV generation is lower, as shown in Tab.III. Humidity is the main factor for comfortable level in comparison of all the results. Additional dehumidification devices would be necessary in building 2 for Shanghai climate, as Fig.11 shows. The similar situation is also happened in building 1 for Madrid, the HVAC is not enough to maintain the humidity at a reasonable level, as shown in Fig.10. So some small scale humidification devices for bedroom would be necessary in building 1 for Madrid.

For building 1, because electricity-driven CO_2 heat pump is the core of the whole system, the influence of weather conditions on indoor environment is lower than that for the independent solar thermal-driven AC. It means the feasibility of HVAC system to different climates is good. Fig.9 and Fig.10 show that temperature comfort demands in Shanghai and Madrid can be met. But dependence on electricity for building 1 is bigger than that for building 2. And use of HRV (heat recovery ventilator) can reduce the humidity level of supply fresh air in Shanghai. But it is not helpful in Madrid.

For building 2, since the house is specially designed for Madrid, the cooling concept operates more efficiently in Madrid. As expected, in the humid climate of Shanghai, the indirect evaporative cooling is less efficient and the ventilation tower cannot be operated. Night sky temperatures are higher in Shanghai (overcast sky). Therefore the radiant cooling system is much less efficient than in Madrid. The PCM ceiling cannot always be regenerated during the night and the heat rejected from the chiller is not dissipated efficiently. Due to high temperatures in the heat sink tank, “free cooling” cannot be used as much as in Madrid and the chiller COP is lower. The cooling coil of the AHU has to be used in Shanghai in order to provide additional cooling and dehumidify the supply air.

8. PRIMARY ENERGY PAYBACK TIME

A life cycle analysis of the house has been done for the building 2 in order to calculate the primary energy payback time of the house for both climates. The total fossil primary energy necessary for materials and system technology (PV, solar thermal, HVAC…) has been estimated to 890 GJ. 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 house construction is then 610 GJ which gives 3026 kWh/m², as Fig.13 shown.

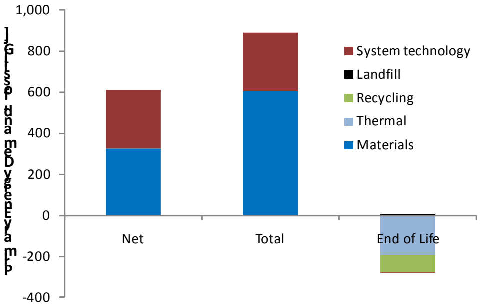

Figure 13: House primary energy demand

Based on this calculation result and the simulated energy demand during operation, the primary energy payback time can be calculated. Primary energy factors (PEF) for the conversion from to electricity to fossil primary energy are needed for this calculation. The conversion factors of GEMIS have been used to consider the electricity mix generation of Spain and China. GEMIS is a life-cycle analysis program and database for energy, material, and transport systems [13]. The calculation equation can be seen in Eqs(1). The calculation result can be found in the Tab.IV. The primary energy payback times of building 2 for Madrid and Shanghai climates are 10.1 and 17.9 years, respectively.

$$N_{PE} = \frac{Q_{house}}{(Q_{PV} - Q_{cons}) \times PEF} \qquad (1)$$

Table IV: Primary energy payback time

	Madrid	Shanghai
PEF elec. mix (kWh_{pe}/kWh_{end})	2.19	2.20
PE payback time (year)	10.1	17.9

9. CO_2 EMISSIONS SAVINGS

Once the primary energy needed for the house has been recovered, the CO_2 equivalent emissions savings during the rest of the house lifetime can be estimated. The conversion factors of GEMIS for Spain and China electricity mix have been used. The other conversion factor from one China research [14] is also used as a reference. A house lifetime of 40 years has been used for the calculations.

Table V: CO_2 emissions equivalent savings

	Madrid	Shanghai	
		GEMIS	MOST
CO_2 factor (kg/kWh_{el})	0.478	0.813	0.921
Total CO_{2eq} emissions saving (kg)	54745	75563	78838

10. CONCLUSION

The energy balance simulation result shows that the electricity generation of PV can meet the demands of two ZERB models in Shanghai and Madrid. Indoor comfortable results show that the temperature comfort can be met for two models under Shanghai and Madrid's weather. But humidity comfort demand need more customized energy concept's design schemes for different weather, such as, dehumidification device for Shanghai or humidification device for Madrid. Calculation results shows that primary energy payback time of ZERB in Madrid is 10.1 years and CO_2 emission reduction is 54745 kg in building lifetime.

Acknowledgment:

The authors would like to express their gratitude to the Science and Technology Commission of Shanghai Municipality for their financial support (Project No.09160702300) and the Robert Bosch Foundation for their financial support within the German-Chinese research cooperation.

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