

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

S. Deng¹, A. Dalibard², M. Martin², Y.J. Dai^{1*}, U. Eicker², R.Z. Wang¹

¹*Institute of Refrigeration and Cryogenics, Shanghai Jiao Tong University, Shanghai,
200240 P R China, yjdai@sjtu.edu.cn*

²*Research Centre zafh.net, University of Applied Sciences, Stuttgart, D-70714,
Germany*

Abstract

Energy supply concepts for zero energy residential building (ZERB) in Shanghai (humid) and Madrid (dry) are discussed in this paper. Simulation is employed as the main research method. Two typical housing models are designed according to the real occupancy condition, the life schedule, the thermostats settings, etc., for the two cities. An energy analysis considering the annual balance of input from the grid and output from renewable power systems is made. Indoor comfortable comparisons between the two models are presented to show optimal design strategies for HVAC under different weather conditions. Also performed is the analysis on the primary energy payback time and the CO₂ equivalent saving in order to evaluate the performance of novel energy systems to verify the feasibility.

Keywords: net zero energy building, solar energy, simulation, building evaluation, CO₂ emission reduction

* Correspondence to: Prof. Y.J. Dai, Tel: (86-21) 34204358, E-mail: yjdai@sjtu.edu.cn

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
N_{PE}	primary energy payback time, year
N_{LT}	house life time, year
F_{CO_2}	CO ₂ conversion factor, kg/kWh
PEF	Primary energy factor, kWh/kWh
M_{total}	Total CO ₂ equivalent savings, ton
Fac	facade
Win	window

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. P. Norton and C. Christensen [1] introduced their design concepts about an affordable zero energy home which was built in cold climates. Four kinds of heating systems, including: ground-coupled heat pump, ERV and natural gas furnace, etc, are considered during design process for heating system. In order to reach the “affordable” purpose, PV cost should be reduced. So the design result is trend to use furnace and electricity resistance for heating. J. Steinbock, et al [3], also chose a

ground source heat pump (GSHP) in energy concept for one net zero energy building. Besides GSHP, energy recovery ventilator and 135.3 m² PV are applied to achieve the “net zero” purpose. The real test data in 2005 showed that building produced 2573 kWh more than it used. Reference [2, 4-5] all applied TRNSYS as the main simulation soft to evaluate the feasibility for net zero energy purpose. The sameness of these three simulation works are that they all chose GSHP as main device in energy supply system so that the energy consumption of building can be limited to a low level and “net zero energy” aim can be easier to realize. Y. Higuchi, et al [6], calculated primary energy consumption for a 106m² net zero energy house under Japan weather condition and life style. Unit air conditioner is chosen as main HVAC system and 34 m² PV are utilized. Most of the NZEB designs have some shortcomings and limitations. First is that there are less innovations in energy supply system. Actually energy supply system, especially HVAC and domestic hot water (DHW) system, takes a high proportion in the whole energy consumption of building. Significant energy saving can be achieved with much deliberate design. Second, the comparisons in energy technologies and design experience are lack. The design experience can not be easily shared because of local characteristic, such as climate or life style. Third, 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.

2. Description of two ZERB cases and energy system concepts

The first case of ZERB is an apartment which will be built on the third floor of a green building in the campus of Shanghai Jiao Tong University [7]. Its indoor function was designed according to China typical apartment for a family with one couple and 1kid. 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 took 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 Table 1.

For shanghai building, 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. The main parts of this device are a small solar assisted hybrid Libr absorption chiller and a CO₂ heat pump. Use of solar thermal driven Libr absorption cooling can dramatically improve the performance of the hybrid heat pump system. It also means that electricity consumption of this device can be reduced to a low level by solar energy input. In summer, the solar thermal energy is collected by heat pipe evacuated tube solar water collectors for 30m². 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 (70m²). If water temperature of collector tank is not high enough, the heat pump is operated to provide heating to storage tank. Then the thermal energy can be transferred to the indoor HVAC terminal units. In cloudy or rainy days, 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. **The layout of system is shown in fig.3.**

For Madrid building, 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 fig. 4 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.

3. Weather data and building internal gain

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 humid for whole year. The mean relative humidity in summer of Shanghai is above 80% and keeps at a high level for whole year. On the contrary, the lowest value of mean relative humidity in Madrid is less than 40% in July. The dry climate dominates the summer of Madrid. Fig.6 shows global horizontal irradiation of two cities for a whole year. The average level of Madrid is better than that of Shanghai, especially in summer.

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

4. Simulation results and discussion

Two detailed models about the house and their equipments 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 2.

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). There are result points for 8760 hours in every figure

based on the whole year hourly simulation. One parameter, namely comfortable zone fraction (CZF), which stands for how many result points are inside the comfortable zone are defined and calculated. By CZF, affect from HVAC system to comfortable level of indoor environment can be evaluated. Similarly, comfortable temperature fraction (CTF) is defined to show how many points are inside the comfortable temperature range (20-26°C). The simulation results for these two parameters are both shown in the Table 2.

Compared to building 1, the energy consumption of building 2 is smaller, not only because the better passive design, 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 Table 2. Humidity is the main factor for comfortable level in comparison of all four results. The CTF and CZF in Table 2 show that indoor environment of four cases have better temperature level than humidity level. That is because two HVAC systems both apply temperature control as main control strategy. So the main control aim for four cases is met based on the CZF results. Additional dehumidification devices would be necessary in building 2 for Shanghai climate, as Fig.11 shows. The similar situation 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 CO₂ 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 air conditioning. It means the feasibility of HVAC system to different climates is good. Fig.9, Fig.10 and Table 3 show that CTFs for Shanghai and Madrid are 96.8% and 92.7%, respectively. 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 has less helpfulness 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. CZF for Madrid is 46.7%, which is the highest one among four simulation cases.

5. Evaluation

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 shown in Fig.13

Based on this calculation result 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 [13] 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. The calculation equation can be seen in Eqs(1). The calculation result can be found in Table 3. The primary energy payback times of building 2 for Madrid and Shanghai climates are 10.1 and 17.9 years, respectively.

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

Once the primary energy needed for the house has been recovered, the CO₂ equivalent emissions savings during the rest of the house lifetime can be estimated, as Eqs(2) shown. The conversion factors of GEMIS for Spain and China electricity mix have been used. The other conversion factor from one China research result [14] is also used as a reference. A house lifetime of 40, 50, 60 and 70 years have been used for the calculations. The results in the Table 4 show that total CO₂ equivalent savings of Madrid building is 74.4 ton during the 50 years. For shanghai building, the total CO₂ equivalent savings is more than 100 ton.

$$M_{total} = F_{CO_2} \times Q_{cons} \times (N_{LT} - N_{PE}) \quad (2)$$

For Madrid, N_{PE} can be accepted, but for shanghai, it is beyond the reasonable range. The reason is that the energy concept designed for building 2 under dry

weather doesn't have a good adaptability to humid weather although building 2 has a good passive energy-saving design. The electricity consumption of building 2 under shanghai weather is 9.8 % higher than that under Madrid weather, but the electricity production under shanghai is 25.4% lower than that under Madrid weather. So N_{PE} for shanghai is 77.2% longer than that for Madrid. From the Eqs(2), Table 3 and 4, it can be seen that the difference between electricity consumption and production of building 2 for Madrid is 43.2% higher than that for Shanghai, although total CO₂ equivalent savings of building 2 for Madrid is lower than that for Shanghai. Increasing the PV capacity to increase Q_{pv} is one solution to reduce N_{PE} and to increase the total CO₂ equivalent savings for Shanghai. If N_{PE} of building 2 under Shanghai weather is limited to 10 years, 120 m² PV is needed at least based on the simulation result. At the same time, cost and envelopment area of building need to be considered according to real application. Besides, improvement on HVAC system and building passive design is the other method to increase the difference between Q_{pv} and Q_{cons} . Considered that the building 2 already has a good thermal insulation performance, some improvements on the dehumidification system can be thought as a useful method, like using some renewable energy driven dehumidifies systems. Humidity load is met by small-scale independent dehumidification system can increase indoor comfortable level and reduce the electricity consumption of existed HVAC system. The added initial cost can be offset by decrease on HVAC capacity and operation fee.

6. 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 CO₂ equivalent saving is 74.4 ton during 50 years building lifetime.

Acknowledgment:

The authors would like to express their gratitude to the National Key Technologies R&D Program (Project No. 2008BAF12B01), the Science and Technology Commission of Shanghai Municipality (Project No.09160702300) for their financial support and the Robert Bosch Foundation for their financial support within the German-Chinese research cooperation. The work would not have been possible without the very engaged project leadership of architectural faculty headed by Prof. Jan Cremers and Sebastian Fiedler.

References

- [1] P. Norton, C. Christensen. A cold-climate case study for affordable zero energy homes. In: Proceedings of Solar Energy, 2006. p. 585-590.
- [2] A. Biaou, M. Bernier, F. Yan. Simulation of zero net energy homes. <http://perso.univ-lr.fr/fcherqui/IBPSAmars2006/12_MBernier.pdf> (Last access: 21/06/2010).
- [3] J. Steinbock, D. Eijadi, T. McDougall, Net zero energy building case study: science house, ASHRAE Transitions 2006; 113, 26-35.

- [4] O. Siddiqui, A. Fung, H. Tse, D.H. Zhang, Modelling of the net zero energy town house in Toronto using TRNSYS, and an analysis of the impact using thermal mass. In: Proceedings of Energy Sustainability, 2008. p. 297-304.
- [5] L.P. Wang, J. Gwilliam, P. Jones, Case study of zero energy house design in UK. Energy and buildings 2009, 1 41(11), 1215-1222.
- [6] Y. Higuchi, M. Udagawa, M. Sato, Design and performance prediction of a zero energy house. In: Conference of Renewable Energy, 2010. No. O-AT-2-5.
- [7] S. Deng, R.Z. Wang, Y.J. Dai, X.Q.Zhai, J.R.Shen, Green Energy Building inside the Campus of Shanghai Jiao Tong University. In: The 6th International Symposium on Heating, Ventilating and Air Conditioning, 2009. p. 50-57.
- [8] Website of the Stuttgart University of Applied Sciences contribution for the Solar Decathlon Europe competition. <<http://www.sdeurope.de>> (Last access: 21/06/2010).
- [9] Official website of the Solar Decathlon Europe competition. < <http://www.sdeurope.org>> (Last access: 21/06/2010).
- [10] Meteotest. Meteororm. Version 6.0. < <http://www.meteotest.ch>>. (Last access: 21/06/2010).
- [11] TRNSYS. A Transient System Simulation Program. Version 16. < <http://www.trnsys.com>>. (Last access: 21/06/2010).
- [12] J. Schumacher. Digitale Simulation regenerativer elektrischer Energieversorgungssysteme, Dissertation, Universität Oldenburg, 1991.
- [13] GEMIS, Global Emission Model for Integrated Systems. Version 5.5. <<http://www.gemis.de/en/index.htm>>. (Last access: 21/06/2010).
- [14] G. Wang, X, Feng. CO₂ emission reduction through energy integration (in Chinese), Chemical industry and engineering progress, China (Beijing), 2006.

Figures:

Fig.1 Concept design of building 1

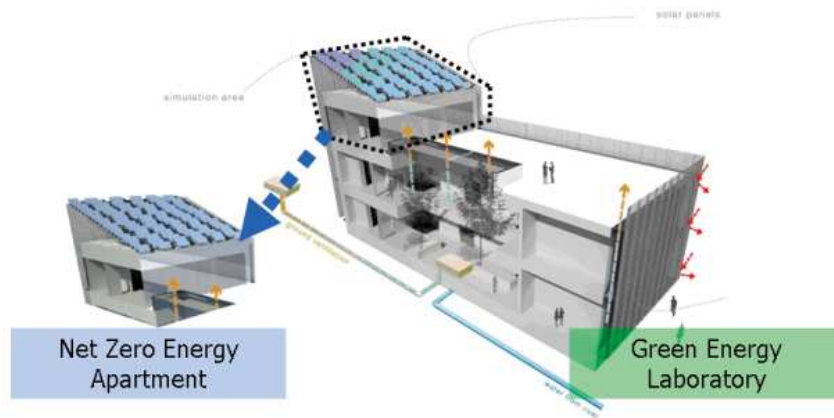


Fig.2 Computer rendering of building 2

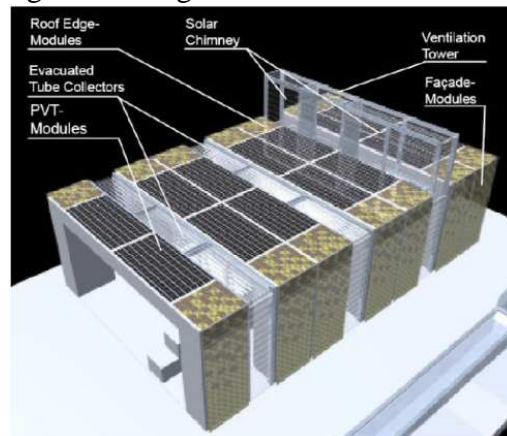


Fig.3 Layout of HVAC system for building 1

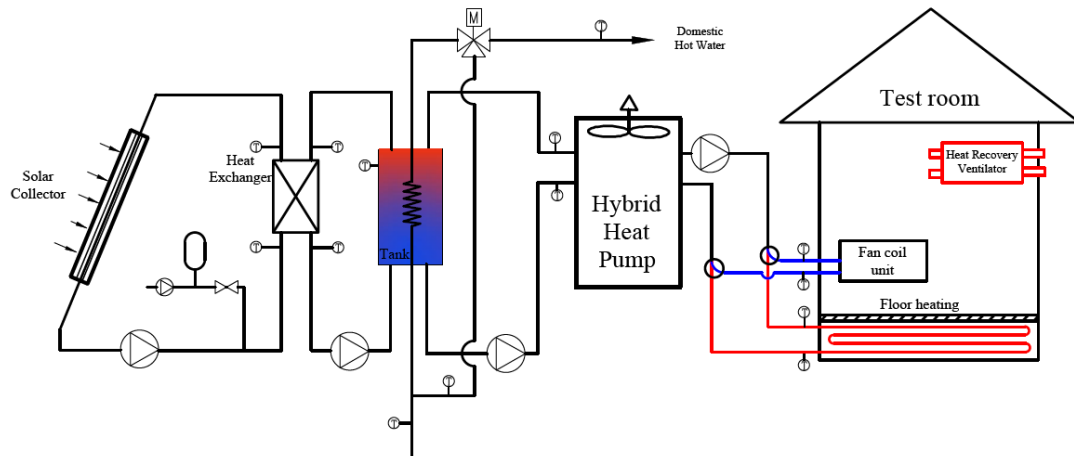


Fig.4 Hydraulic scheme of energy system for building 2

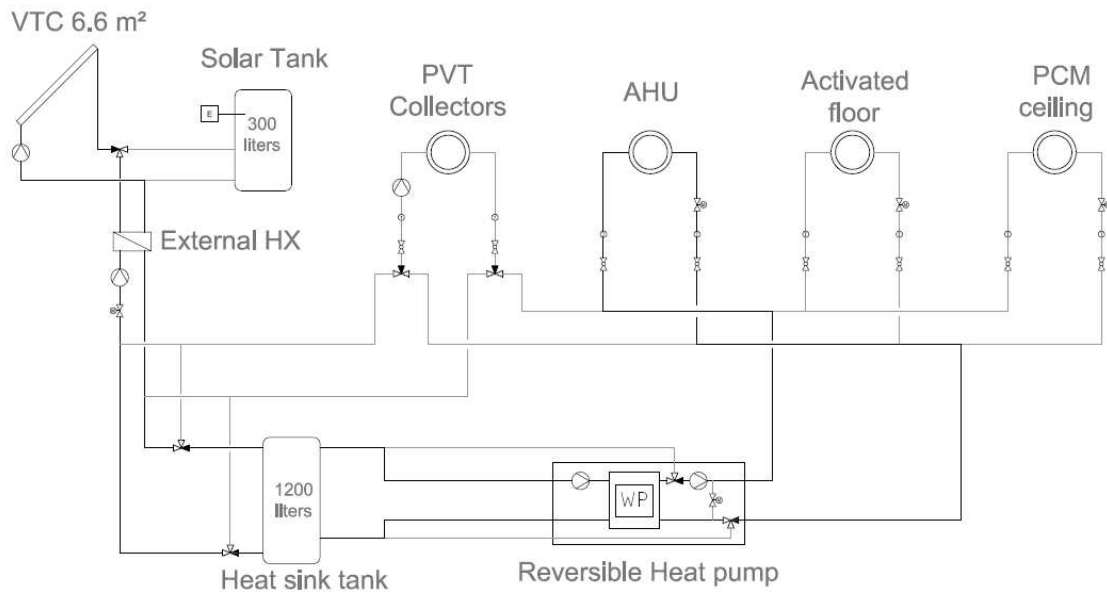


Fig.5 Mean ambient temperature and relative humidity comparison between Madrid and Shanghai

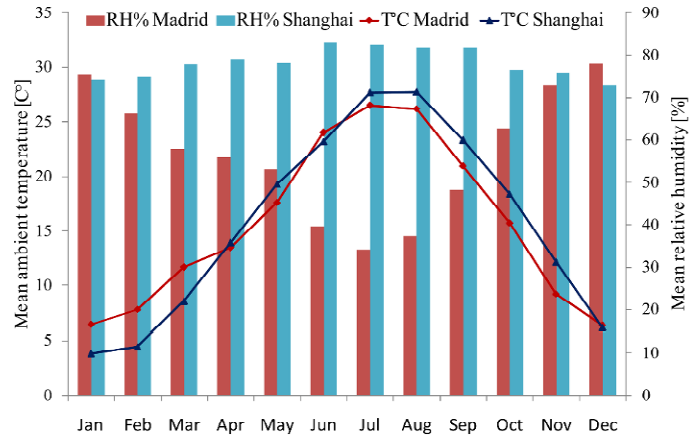


Fig.6 Global horizontal irradiation comparison between Madrid and Shanghai

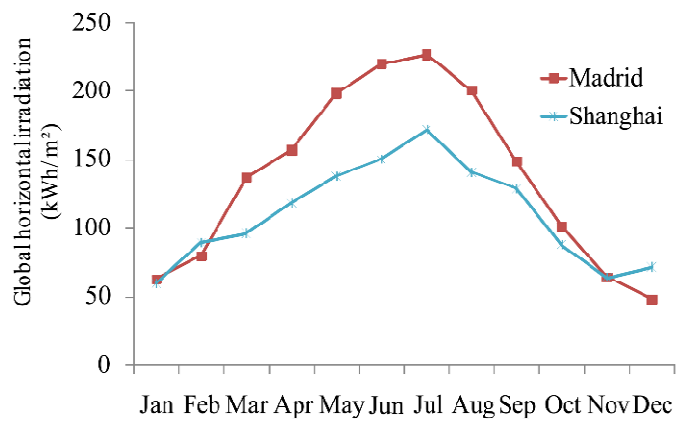


Fig.7 Thermal gains of building 1

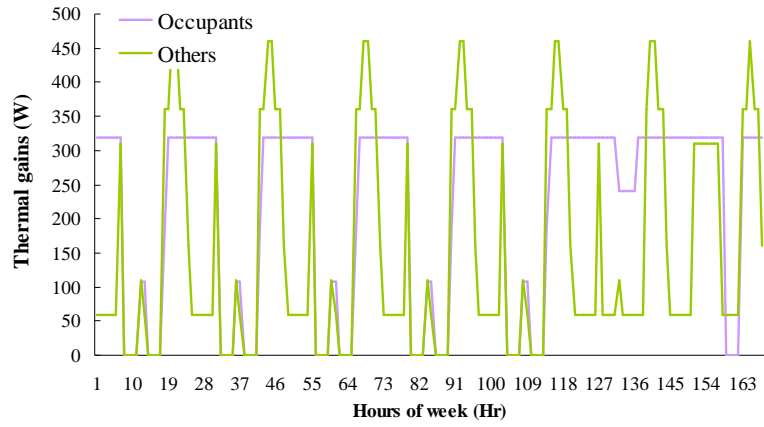


Fig.8 Thermal and humidity gains of building 2

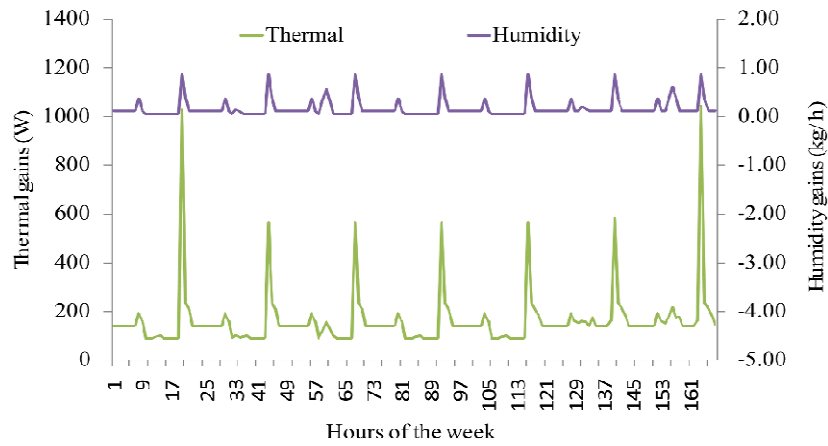


Fig.9 Building 1 result (Shanghai)

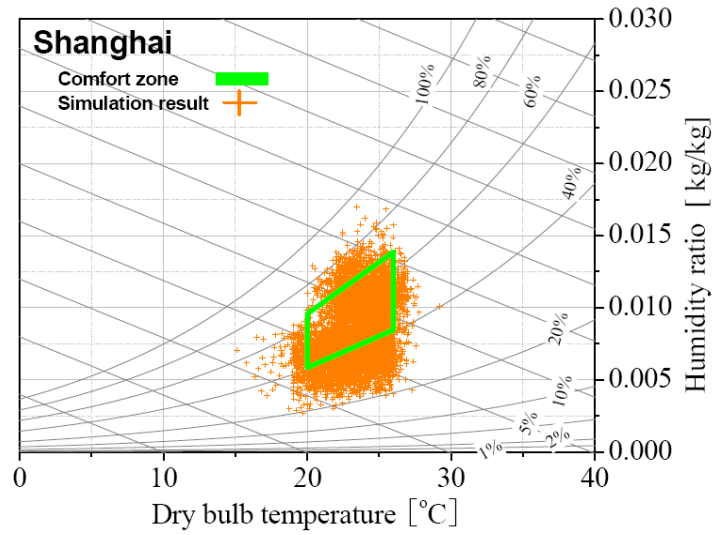


Fig.10 Building 1 result (Madrid)

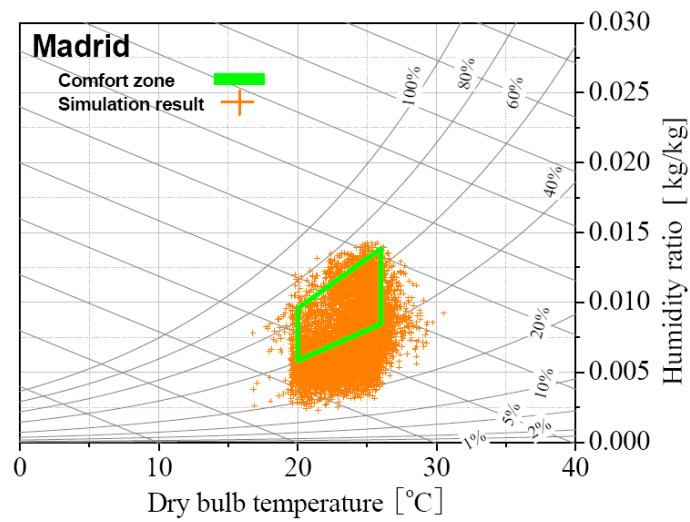


Fig.11 Building 2 result (Shanghai)

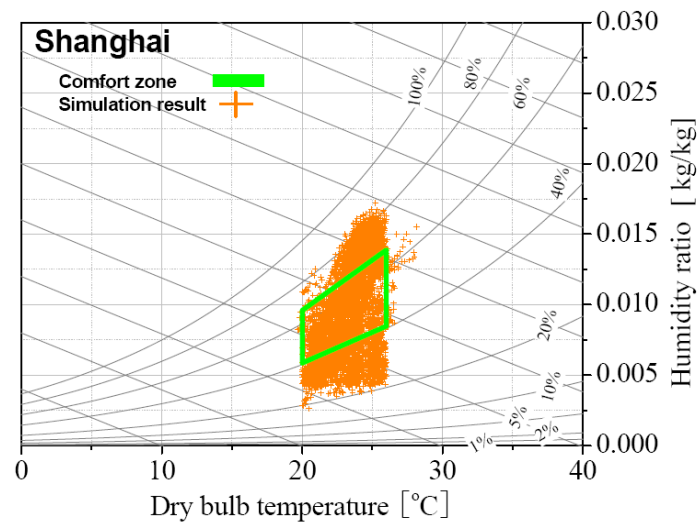


Fig.12 Building 2 result (Madrid)

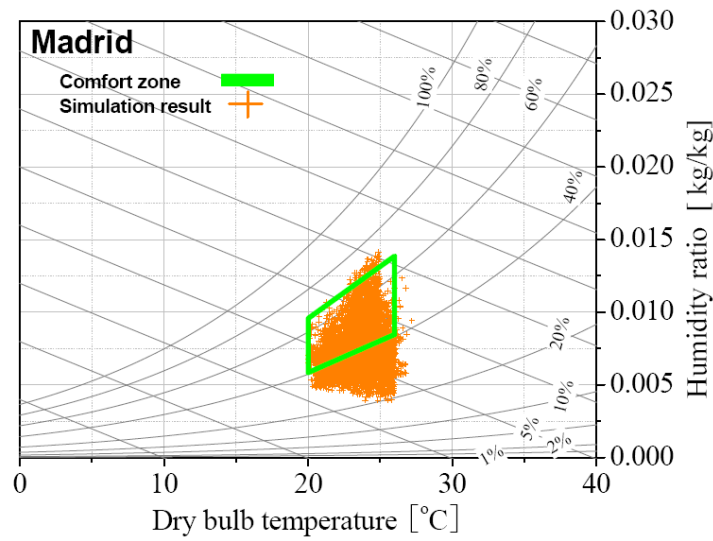
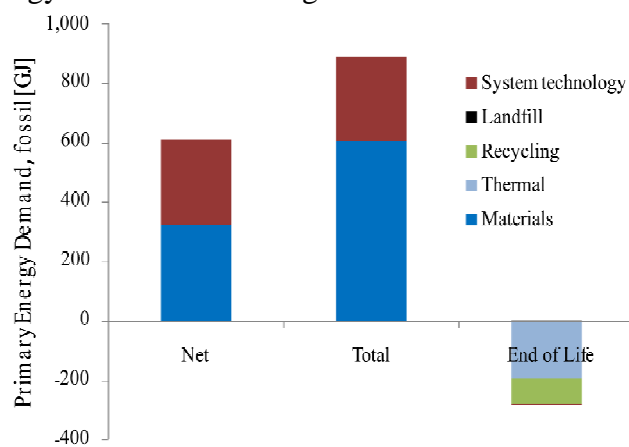


Fig.13 Primary energy demand of building 2



Tables:

Table 1: Passive design of two buildings

	Building 1 (designed for Shanghai)			Building 2 (designed for Madrid)		
	Surface [m ²]	U value [W/(m ² K)]	G value [-]	Surface [m ²]	U value [W/(m ² K)]	G value [-]
Floor	93	0.30	-	56	0.1	-
Fac. S	45.9	0.31	-	16.6	0.13	-
Fac. N	45.9	0.31	-	16.6	0.13	-
Fac. E	32.6	0.31	-	22.8	0.16	-
Fac. 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,		

Table 2: Simulation 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
Comfortable temperature fraction (%)	96.84	92.76	99.37	99.07
Comfortable zone fraction (%)	45.58	38.62	46.76	40.27

Table 3: Primary energy payback time for building 2

Location	Madrid	Shanghai
PEF _{elec. mix} (kWh _{pe} /kWh _{end})	2.19	2.20
N _{PE} (year)	10.1	17.9

Table 4: CO₂ emissions equivalent savings for building 2

Location	Madrid	Shanghai GEMIS	MOST	
CO ₂ factor (kg/kWh _{el})	0.478	0.813	0.921	
Total CO _{2eq} emissions saving for different life time (kg)	40 years	54745	75563	78838
	50 years	74430	109755	124335
	60 years	93084	143946	163068
	70 years	111738	178138	201802