Energy and Buildings 58 (2013) 19–26

Contents lists available at SciVerse ScienceDirect

Energy and Buildings

journal homepage: www.elsevier.com/locate/enbuild

Solar water heating system integrated design in high-rise apartment in China

Jie Shi[a,*], Wei Su[b], Mingya Zhu[c], Huaning Chen[d], Yiqun Pan[a], Shui Wan[d], Yawei Wang[c]

[a] Sino-German College of Applied Sciences, Tongji University, 1239 Siping Road, Shanghai 200092, China
[b] Project Supervision Consultants (Shan Dong) Co. Ltd., China
[c] School of Mechanical Engineering, Tongji University, Shanghai, China
[d] Shanghai Architectural Design & Research Institute Co. Ltd., China

ARTICLE INFO

Article history:
Received 23 July 2012
Received in revised form
28 September 2012
Accepted 7 October 2012

Keywords:
Solar energy
Heating
Integrated design
High-rise apartment

ABSTRACT

With the development of urbanization in China, more and more high-rise residential buildings are constructed, mostly with 10–15 stories. Solar water heating system has been widely used in low-rise residential buildings in China, while its application in high-rise apartment is still in the initial stage. In this paper, the current application situation of solar water heating system in urban residential buildings of China is investigated. Additionally, demonstration projects of high-rise residential building are introduced, in which the application feasibility and limitation of solar water heating system are emphasized and some appropriate planning types of that are discussed. Finally, this paper analyzes the applicability of solar water heating systems integrated design in typical high-rise apartments from various aspects (such as architectural elevation, architectural plane and detailed construction) in the planning and designing phase.

1. Introduction

In 1958, solar water heater was first employed in China. The thermosyphon circulation solar water heater developed by Tianjing University was used in a 12.6 m^2 bathroom. Since the energy crisis in the 70s, renewable energy utilization has become a hot-spot issue around the world. Chinese government formulated a series of policies and regulations to encourage the development and application of solar water heater in the late 1970s. Later in 1987, the first all-class evacuated solar collector tube was produced in China and its industrial mass production was realized soon, which established the foundation of large-scale industrialization. The solar energy industry entered the primary stage since 1993 when the evacuated tubes occupied quite a large proportion of the market. With the rapid development of solar energy industry from 2001 to 2006, compact all-glass evacuated solar tube collectors had the majority of the market [1]. At present, the application of solar water heater in low-rise and multistoried residential buildings expands ceaselessly, from group buildings (see Fig. 1) to residential districts, villages and towns (see Fig. 2). The production of solar water heaters increased from 3.5 million m^2 in 1998 to 125 million m^2 in 2008, respectively with the annual average growth rate of 25% and 24%. Simultaneously, the area of solar water heaters per thousand people reached 96 m^2. It is well known that China has become the largest producer and consumer market of solar water heaters in the world, with the total output and storage capacity more than half of total world production, ranking first in the world [2].

There are two important issues involved in the integration of solar water heating system and building design. One is about solar water heating system, which is composed of solar collector, water storage tank, as well as water pipeline. In China evacuated tube solar collectors have been often applied in buildings, while in Europe flat plate solar collectors are more common. Although these two types of solar collectors have their own advantages and disadvantages in terms of technical performance, the flat plate collectors are more suitable for pressure system and secondary circulating system, easier to be installed, and with longer service life and better compatibility to building appearance. In the field of solar energy system, much research focuses on system performance. Zhai et al. [3] validated the practical energy performance of a solar energy system capable of heating, cooling, natural ventilation and hot water supply in Shanghai by experimental investigation in 1-year operation period. Pantic et al. [4] studied energy performance of three different open loop air heating building-integrated photovoltaic/thermal (BIPV/T) systems that utilize recovered heat for home heating.

The second issue is about the building design. The dominant type of residential buildings in China is high-rise apartment. By contrast, single family house, townhouse and multi-storied apartment are common in Europe and North America. Due to much higher occupancy in high-rise apartment, only installing solar collectors on the roof cannot supply enough hot water as required, therefore building

* Corresponding author. Tel.: +86 21 69584738; fax: +86 21 69589621.
E-mail address: shijie@tongji.edu.cn (J. Shi).

0378-7788/$ – see front matter © 2012 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.enbuild.2012.10.018

Fig. 1. Chang Dao Green Garden in Zhejiang.

façade has to be utilized. This makes demand of the diversity and commercialization of solar collector products from such aspects as type, color, style, property, and size, for the sake of making full use of limited building facade. Standardized design method and process as well as proper design proposals about integrated design of solar energy system for high-rise residential buildings are needed urgently.

Few studies have deeply investigated application of solar energy system on the basis of reasonable and effective integrated design of solar collector and architecture facade construction. When using integrated approach, solar system becomes part of the overall building design. The solar elements are designed as architectural elements in attractive and visible wayside by multi disciplinary design teams with the consideration of esthetic compatibility [5]. Johnston [6] mentioned the advantages of traditional China buildings – roofing (eaves) at each storey, in addition to that on top of the building, for application of integrated solar energy system from the point of building morphology, considering solar energy collection and shading, as well as their matching to temporal and locational variations in energy demand. Then he discussed the energy saving potential of building-integrated solar system by comparing primary energy demand of solar-integrated building with that of similar building without solar panels. Considering different energy demand in different climatic condition, calculations were made for Beijing in winter, as an example of high space heating demand, for Hong Kong in summer, as an example of high air conditioning demand, and for Shanghai, as an intermediate example.

Fig. 2. Bolitai Solar village in Pingu in Beijing.

This paper discusses the applicability of solar water heating systems integrated design in typical high-rise apartments in China from such aspects as architectural facade, architectural plane and detailed construction in the planning and designing phase, based on the investigation on current situation and demonstration projects.

2. High-rise residential buildings in China

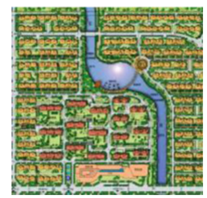
With the development of the urban residential construction, the urban population has been rising, which is more than 600 million by the end of 2008, rapidly advanced urbanization process encourages the fast development in the building industry. In order to keep the balance of urban ecosystem, protect the living environment, and satisfy people's increasing level of demand, it is an inevitable trend to build more and more high-rise residential buildings. Because of the situation of economic foundation and the social culture atmosphere in China, Urban residential buildings always have features of high-rise and high-density, especially in hot-summer and cold-winter zone. For example, in Shanghai, the number of high-rise buildings increases very fast due to the regional high population density and high housing prices [7]. As high-rise office buildings are becoming saturated, the construction of high-rise residential buildings appears to be on the rise. With the very big scale and fast speed residential building construction, energy consumption issue is becoming more and more prominent.

According to the latest statistics, building energy consumption accounted for 27.8% of terminal energy consumption of the whole society in China, which is close to 1/3 in developed countries [8]. Among the total energy consumption, the building sector accounted for 27.6% in 2001 and it is still increasing. It is predicted that the building energy consumption sector will inevitably be about 35% by 2020. Furthermore, building energy consumption per square meter in China is far more than that in developed countries, and this situation will not be change in recent years. Although heating period in China is shorter than other countries, heating energy consumption per square meter in China is still 3–4 times bigger than that in developed countries [9]. However, as Chinese people's living condition is getting better and better, air-conditioning systems are applied in most buildings and domestic hot water is supplied in most urban residential buildings for the purpose of indoor thermal comfort, which brings tremendous potential to the development and application of solar energy in buildings.

3. Architectural layout

The survey shows that south-north orientation, row layout and parallel arrangement are adopted in most residential buildings in China [10]. Table 1 displays the architectural layout of the typical existing high-rise residence communities using solar water heating systems in China. Note that, the distance between the buildings in these residence communities is calculated according to the local sunshine standard requirements. For example, in Shanghai, as specified in "Code for Planning and Design of urban Residential Areas" (GB50180-93) and "Technical Regulations of Urban Planning and Management in Shanghai", the distance between buildings must be designed to ensure no less than one hour sunshine time for each bedroom (more than one bedroom each family) of residential buildings on the winter solstice. As for buildings using solar water heater, the distance between them should be designed to meet the demand that the building envelope installed the solar collector can get no less than four hours sunshine duration in order for preferable performance of solar collectors [11].

Table 1
Architectural layout of high-rise apartments using solar energy in China.

Project name	Sanxiang Siji flowery district in Shanghai	Zhongyi Baodi in Changzhou	Yihao Jiayuan in Lingang new city in Shanghai	Weike·River Side Mood in Ningbo	The second period of ecological city of world exposition in Kunming
Geographical position	120°51′E, 30°41′N	119°8′E, 31°9′N	120°51′E, 30°41′N	120°55′E, 28°51′N	102°10′E, 24°23′N
Sunshine duration	1638–1930 h/year	2047 h/year	1638–1930 h/year	1848 h/year	2250 h/year
District planning					
Architectural layout					

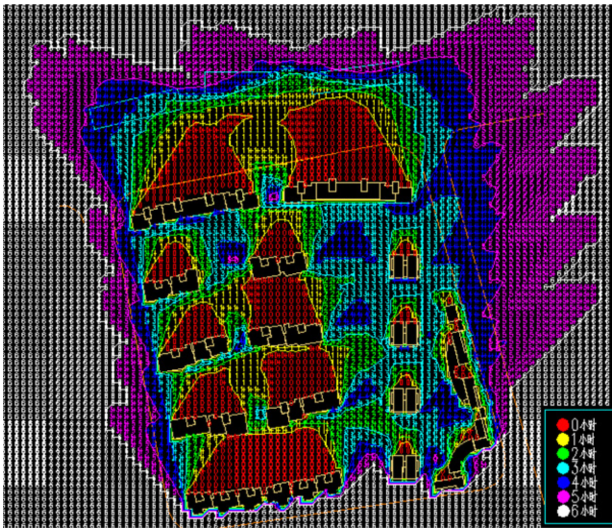


Fig. 3. Simulation analysis of sunshine duration in a district at winter solstice.

Indeed, it is difficult to ensure that the southern facade is shading by buildings in front of it and that the lower part of facade can receive 4 h sunshine time even if the distance between the buildings is designed based on sunshine standard. It is commonly found that solar water heaters are least likely to be obscured by other buildings when installed on the roof. However, it is extremely difficult to satisfy all the residents' requirements for solar energy utilization with the rapid improvement of building height. With the increasing of the residents, the pipes have to be correspondingly added, while there is no change of roof areas. Thus, in order to optimize the utilization of solar energy, the impact of architectural layout on performance of solar radiation absorption by building surface should be considered early in the district planning [12].

To the whole residence community, the sunshine condition of point-block residence (whose aspect ratio of architectural plane is less than 1) and slab-block residence (whose aspect ratio of architectural plane is bigger than 1) are different, as Fig. 3 shows. The point-block building usually has shorter width and bigger height than others. So it is easy to meet the requirement of 1 h sunshine duration in the winter solstice, while hard to satisfy the need of 4 h sunshine on building surfaces. It is observed that most of building southern facade is obscured from 10:30 a.m. to 14:00 p.m. (showed in Fig. 4) and this facade can only receive one hour of sunlight from 9:00 to 12:20 a.m., while it is the most efficient period during 10:00 a.m. to 14:00 p.m. for solar collectors to obtain solar energy in a day. As for slab-block residence, the probability that the building

Fig. 4. Occlusion of south elevation for slab block buildings at 10:00 a.m.

Fig. 5. Occlusion of south elevation for point block buildings at 10:00–11:00 a.m.

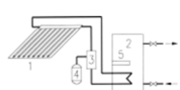
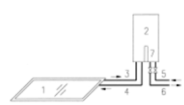
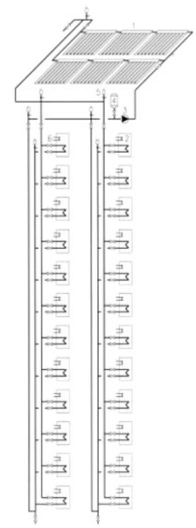
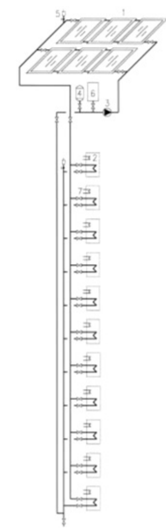
northern facade can be occluded by the building southern facade increases as the length of buildings grows (showed in Fig. 5). Therefore, the building with longer length is usually arranged on the north end of the residence community and near to road, which has little influence on buildings on the other side of the road to receive sunlight. In addition, some vegetation 5–10 m high may also affect the solar duration at the lower floors of buildings. Consequently, the length of residential buildings is restricted with different building height in Shanghai. For instance, the maximum projection length of the building consecutive unfolded width should not be more than 60 m if the building height is over 60 m [13]. Despite all that, the distance between the buildings specified according to regional standard or national standard can yet hardly satisfy the requirement of lower floors of high-rise residence for solar duration to use solar water heaters.

4. Solar water heating system

Three types of the solar water heating system are usually applied in high-rise residential buildings: central hot water system, central-distributed hot water system and distributed hot water system. Collectors of central and central-distributed hot water systems are usually installed on the roof where sufficient space must also be necessary. With the increase of floor, residents and users, larger area of solar collector is needed. Therefore, there may have no enough space on a building roof to install collectors when the central system or central-distributed system is applied alone. To solve this problem, solar water heating system is only applied to higher floors, while electric water heaters or gas water heaters are applied to lower floors in some projects with high-rise residential buildings However, it will cause that there are two different kinds of house type in the housing trade fair and bring about proprietors' doubt about the difference, which is inconvenient to real estate developers.

It is investigated that a combination of central system or central-distributed system with distributed system can solve the above mentioned problem for high-rise residential buildings over 12-storey (as the case may be) (as showed in Table 2). As for the distributed system, the collectors can be installed on the balcony slab or the wall between bedroom windows. Each household has constant area for collector installation, independent of the influence of building height. Accordingly, the distributed hot water system is applicable to different floors of high-rise residential buildings. However, it is still probable for the bottom floors of high-rise buildings that the performance of solar absorption is affected by nearby vegetations and buildings. There are some helpful measures

Table 2
Design cases of solar water heating system used in high-rise apartments.

Project name	Sanxiang Siji flowery district in Shanghai	Zhongyi Baodi in Changzhou	Yihao Jiayuan in Lingang new city in Shanghai	Weike·River Side Mood in Ningbo	The second period of ecological city of world exposition in Kunming
Story number	14 or 18 story	9–28 story	12 story	10–19 story	9–12 story
Type of system	Individual hot water supply system	Individual hot water supply system	Collective-individual hot water supply system	Collective hot water supply system	Collective-individual hot water supply system
Principle chart of solar heating water system	 1-Solar collector 2-Storage r tank 3-Solar energy station 4-Expansion tank 5-Auxiliary electric heater	 1-Solar collector 2-Storage r tank 3-Medium input tube 4-Medium output tube 5-Cold water pipe 6-Hot water pipe 7-Auxiliary electric heater	 1-Solar collector 2-Storage r tank 3-Heat collecting circle pump 4-Expansion tank 5-Automatic exhaust valve 6-Auxiliary electric heater	 1-Solar collector 2-Storage r tank 3-Heat collecting circle pump 4-Hot-water supply return pump 5-Automatic exhaust valve 6-Reducing valve	 1-Solar collector 2-Storage r tank 3-Heat collecting circle pump 4-Expansion tank 5-Automatic exhaust valve 6-Intermittent charging box 7-Auxiliary electric heater
Auxiliary energy	Electric heating	Electric heating	Electric heating	Gas or electric heating	Electric heating
Heat collecting pipes layout	–	–	North balcony or stair-room	Well of water meter pipes	North balcony or kitchen
Storage tank location	South balcony	South balcony or shelf for outdoor unit of air conditioner	North balcony or kitchen	Roof	North balcony or kitchen

for this problem, such as increasing the area of collectors, adding the number of evacuated tubes, installing reflector plate additionally to increase heat-collecting efficiency, and so on. For example, distributed hot water system can be applied to the 12th floor and above, while the central water system used for below the 12th floor in a 24-storey residential building. Similarly, distributed hot water system is used for the household with convex balcony, while central hot water system is applied to the household with concave balcony, according to the concavo-convex characteristic of building surfaces. It is important to note that the application of an integrated system may affect the appearance of building elevations, which needs cooperation with architects and other designers from the global perspective.

5. Solar heating system and building design

Commonly solar water heating system is mainly composed of the solar collector, the distribution pipe and the storage tank. The placement of storage tank and distribution pipe should be matched with the architectural design, which has great influence on the utilization of solar energy in buildings. For example, for a residential building with three households on one floor in Shanghai, here provides two options of layout scheme of solar water heating system. One is distributed solar water heating system with single-household solar collector installed on the balcony, as the placement of storage tank and distribution pipe showed in Fig. 6. It should be taken into consideration that whether the balcony surface will be blocked by the convex part of the building. The other is central solar water heating system with central solar collectors placed on the roof (as showed in Fig. 7). The selection of system type may be determined by both the centralized piping arrangement and the placement of storage tanks (on the balcony or indoors). In the central system, distributed pipes can be centralized in building shafts, which is manageable and has no affect on building facade design.

6. Integrated construction design

The integrated design of building construction and solar collectors plays a key role in the application of solar water heating system in high-rise buildings. In this investigation, both flat-plate solar collectors and evacuated tube solar collectors have their advantages and drawbacks that should be correctly understood. How to make the most of the advantages and minimize the drawbacks is the first challenge in the integrated design process. Obviously, flat-plate

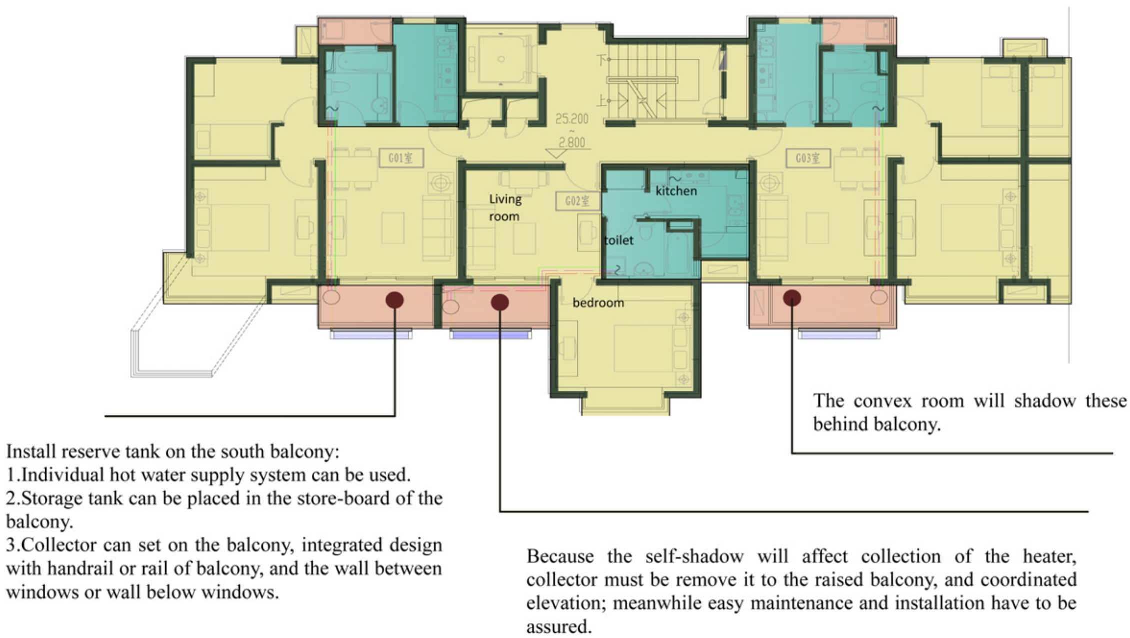


Fig. 6. Plane distribution of distributed solar water heating system applied in one floor with three households.

solar collectors are more suitable for the sloping roof or roof truss. While for vertical surfaces, the heat-collecting efficiency of flat-plate collectors is less than evacuated tube collectors because the application of flat-plate collectors is limited by certain requirement of solar incidence angle. The evacuated tube collector is consisted of circular evacuated tube and can be embedded on the surface of balcony slab or the wall between windows appropriately in different directions (horizontally and vertically), which provides applied advantages from the aspects of shape, size, and building appearance in the integration design of building construction and solar water heating system.

Presently there are three scenarios of integrated design of high-rise residential building and solar water heating system, discussed in Table 3 in detail. In the first pattern, solar water heaters are vertically installed on the balcony as the balcony slab. In this way, the annual heat-collecting efficiency of the collector is less than that of collectors installed with the angle close to geographical latitude. In the second pattern, solar water heaters are placed on the balcony or the window to serve as not only collectors but also shadings. However, the size of cantilever should be calculated according to different local solar altitude angles to satisfy the demands of indoor daylighting. The integration of building roofs is used in the last pattern, which is more suitable for solar energy application in Chinese high-rise apartments than the above two scenarios. The roof is regarded as the fifth elevation of buildings. Currently Chinese architects always highlight building roofs in the form of

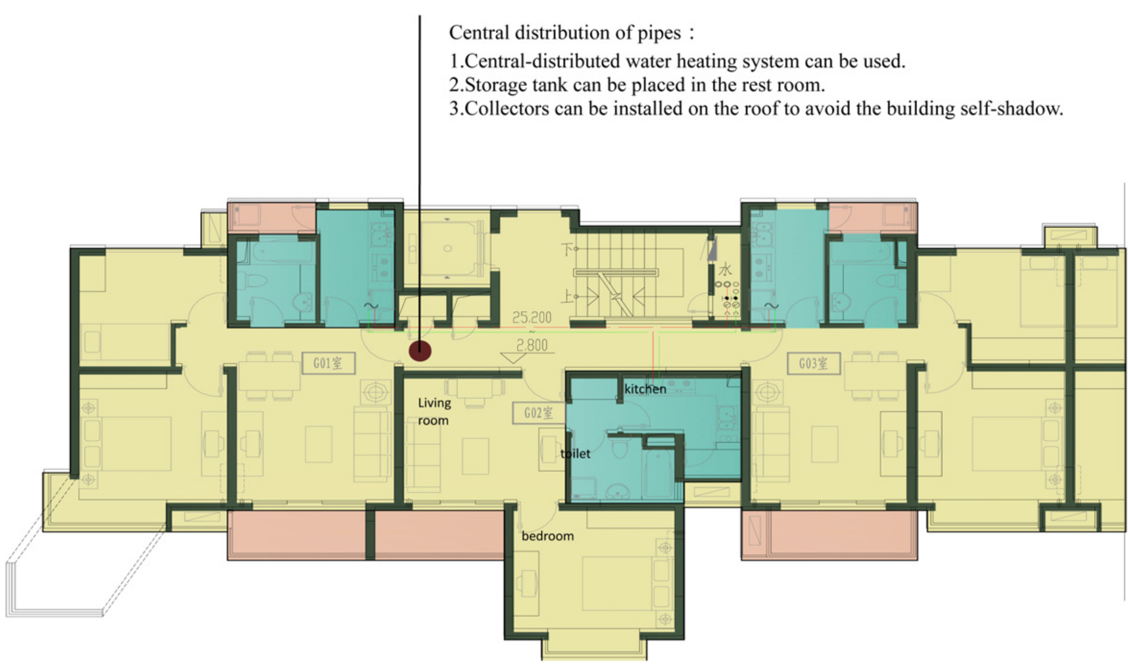
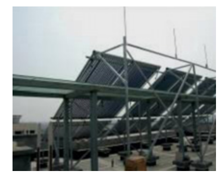


Fig. 7. Plane distribution of central solar water heating system applied in one floor with three households.

Table 3
Design of integrated construction.

Names	Balcony column board	Sun shading board	Roof structural frame		
Appearance					
Incline angle	90°	45°		30°	
Detail construction					
Feature	Integrated with balcony board simple, and easy	Easy to install. Its incline angle is considered by the maximum efficient. But maybe shade the lower collectors.	Metal or concrete trestles are used to install collectors continuously in lines and rows with high efficiency and easy to maintain		
Application scope	2–6 story or high-rise apartment (10 story and higher)	2–6 story or 9–11 story apartment		12–18 story apartment	

distinctive floating board in the design process, showing certain personal or architectural signatures. Solar water collectors can be combined with the floating board design well, and the installation angle and direction of solar collectors can be adjusted based on targeted heat-collecting efficiency. In short, the integrated design should be considered as synonymous with the word "compatibility" [5]. In order to obtain abundant solar energy and optimize building appearance, suitable and flexible system pattern should be selected. At the same time, optimized combination of solar collectors and building construction is of great importance.

7. Discussion

1. Indeed, the distance between buildings that is designed based on relevant standard of Chinese urban residential building can hardly meet the demand of solar duration for solar collectors installed on south elevation. Therefore, the hybrid of certain technologies of solar water heating system should be implemented to satisfy people's hot water demand. In this case, limited building surfaces should be made the most use for solar absorption, which needs corresponding matched design in building plane, building façade and envelope.
2. The difference of solar radiation intensity for different building surfaces and corresponding placement of solar collectors causes the disparity of heat-collecting efficiency of solar water heating systems and hot water supply situation. Even though this disparity between top and bottom floors can be made up by adjusting heat collecting area, available areas on building facades are limited after all. At the same time, this will bring about series of questions, such as shortage of solar collector area, additional requirement of building façade design, different cost of house type with different solar water system and subsequently inconsistent housing standards rates. All above are reasons why real estate developers lack initiative in the application of solar water system. It is expected that the combination of solar energy application and other energy technologies, such as ground source heat pump and bio-energy, can significantly contribute to promote the energy efficiency of the whole building, which should be the focus in the utilization of solar energy.
3. In some cases applied central solar water heating systems in residential buildings, auxiliary heating equipments are usually used and supported by each family, which is convenient to property management. The auxiliary heating system is always designed by 100% of the heating load. At present, electric heaters are the main auxiliary heating equipment. Although gas heaters are more powerful, the obvious obstacles of applications are the expensive price, high demand of hydraulic pressure, potential safety hazard, limited places for installation, and so on. Cold water meter is mostly applied in water metering and charging of solar water heating systems. Owing to the low pressure of municipal water, secondary water pump is necessary to supply the hot water to each storey. In addition, the central solar water heating system is usually maintained by property management companies and the cost is included in property fee.
4. The height of high-rise buildings gets higher, while the roof area remains unchanged. It is extremely difficult to satisfy all residents' requirement for solar energy utilization. Consequently vertical façades should be made the most use to install solar collectors, which may have certain affect on building appearance. The integrated design of architectural appearance, building elevation, building plane together with solar water heating system is of great importance and should be considered in early planning and design stages. In fact, solar system technology is relatively mature, while the key point of application is "integration design" combined with architectural design. The primary challenge is that how to make use of building facades on the basis of optimizing architectural appearance and utilization of enough solar energy.
5. It is a prerequisite that benefit-based incentive policies and regulations formulated by national government to promote the development of solar energy building, which is verified in the practice of developed countries. The evaluation criterion of building solar energy performance is an effective measurement of building sustainability and is necessary to promote the implementation of market-based energy-efficient building certification. The combination of evaluation criteria and integrated design is an essential element during optimized design process. Under challenges of globalization and the reality of our country, a robust appraisal system for sustainable and green building becomes extremely efficient to promote the ecological development of urban construction.

In conclusion, the solar energy utilization should be taken into consideration cautiously, whether in building community planning or detail structure design of the single building. First, site selecting and community planning have decisive effects on energy consumption. Wise planning decisions will not only benefit us now but also leave precious treasure to the future. Moreover, form and plane design of single buildings have effects on both energy efficient performance of the entire community and solar energy utilization efficiency of the limited building external surfaces. During the whole process of architectural design, serviceability and adaptability to buildings should be taken into account seriously in the application of solar energy technology, which means comprehensive consideration of needed materials, system styles, color application and assembling/disassembling performance of solar energy system. These aspects have great influence on building facade design. Meanwhile, exploitation and utilization of building external surfaces will also make the application and development of solar energy technology clear, and promote localization, industrialization and diversification of solar products.

References

[1] National housing and resident's environmental engineering technology research center, Integration Design for Solar Water Heating System in Dwelling, China Architecture and Building Press, 2006, pp. 1–10.
[2] X. Wei, Z. Ruicheng, L. Bin, Report on China Solar Energy in Building, China Architecture and Building Press, 2010, pp. 8–14.
[3] X.Q. Zhai, R.Z. Wang, Y.J. Dai, J.Y. Wu, Y.X. Xu, Q. Ma, Solar integrated energy system for a green building, Energy and Buildings 39 (2007) 985–993.
[4] S. Pantic, L. Candanedo, A.K. Athienitis, Modeling of energy performance of a house with three configurations of building-integrated photovoltaic/thermal systems, Energy and Buildings 42 (2010) 1779–1789.
[5] A.G. Hestnes, Building integration of energy systems, Solar Energy 67 (1999) 181–187.
[6] D. Johnston, Solar energy systems installed on Chinese-style buildings, Energy and Buildings 39 (2007) 385–392.
[7] N. Lansheng, Z. Ying, S. Ping, The 21st Century Chinese Cities' Housing Morphology Analysis, China Architecture and Building Press, 2004, pp. 23–44.
[8] W. Changgui, Z. Ruicheng, The Application of New Energy in Architecture, China Electric Power Press, 2003, p. 18.
[9] http://sh.east-day.com/eastday/shnews/fenleixinwen/chengjian/userobject1ai668574.html
[10] L. Zhenyu, City Housing City: Residential Development Comparison Between Berlin and Shanghai, Southeast University Press, 2004, pp. 160–163.
[11] Technical code for solar water heating system of civil buildings, GB 50364-2005.
[12] E. Mahaek, Solar Effective Envelope Design Advision (SEEDA), Dissertation Abstracts International, Volume: 64-04, Section: A, p. 1108.
[13] Specification of applied technique for solar energy application in civil buildings (fascicule: hot water system), DGJ08-2004A-2006.