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COMPREHENSIVE EVALUATION OF SOLAR DOMESTIC HOT WATER SYSTEMS BASED ON ONLINE MONITORING: A CASE STUDY IN A UNIVERSITY, CHINA

Xie Hui[1*], Li Xiaolin[1], Hao Bin[2], Lu Yuanyuan[2], Liang Wei[1]

1 School of civil and resource engineering, University of Science and Technology Beijing, Beijing 100083, China

2 Shenzhen Institute of Building Research Co. Ltd, Shenzhen 518049, Guangdong, China

ABSTRACT

In order to better understand the real-life thermal performance of Solar domestic hot water (SDHW) systems, SDHW systems installed in dormitories in a university were selected for on-line monitoring. There are 50 dormitory buildings in this university, and each building contains around 430 students. A SDHW system is installed in each building, using the glass evacuated solar tube collector, with an average collector area of 260 m^2. Air source heat pumps are used as auxiliary heat sources in the collector side. All SDHW systems were equipped with data logging system and remotely monitored with online data. Thermal performance analysis and economic analysis of SDHW systems were presented in this paper. The results show that the thermal performance and economy of SDHW systems for dormitory buildings are very good because the domestic hot water demand of student dormitories is relatively concentrated in time and space. Therefore, SDHW systems has a good application prospect in dormitory buildings.

Keywords: solar domestic hot water system, dynamic thermal performance, comprehensive evaluation, dormitory building

NONMENCLATURE

Abbreviations	
SDHW	Solar Domestic Hot Water

1. INTRODUCTION

While energy efficiency has played a significant role in curbing energy consumption in many countries over the last four decades, ever increasing activities in all sectors and inevitable depletion of fossil-based fuel resources make it necessary to find alternative resources [1,2]. The pairing of energy efficiency and renewable energy in meeting future energy demands has been hailed as the most promising pathway for energy sustainability [3,4]. Solar water heating systems are now widely used in various aspects of civil area throughout the world [5-7]. In 2017, 35 GW$_{th}$ of capacity of glazed (flat plate and vacuum tube technology) and unglazed collectors was newly commissioned globally, bringing the total global capacity to an estimated 472 GW$_{th}$ by year's end [8]. The six leading countries for new installations in 2017 were China, Turkey, India, Brazil, the United States and Germany, which were also the top countries for cumulative capacity at the end of 2016, but in a different order [8].

China's solar energy resources are relatively abundant. The total annual solar radiation is 3350~8370 MJ/(m^2·a), with an average of 5860 MJ/(m^2·a), and the annual sunshine number of the area with a land area of 2/3 or more is more than 2,200 hours [9,10]. The use of solar energy to solve the problem of domestic hot water use in urban residential buildings in China can save a lot of energy costs while saving energy, which is of great significance to China. Since the late 1990s, China's solar water heater industry has developed rapidly. After nearly three decades of development, China was the world´s largest solar thermal market and producer by far. In 2017, the area of collectors added in China reached 3723 million m^2 (i.e. 26.1 GW$_{th}$) and the cumulative capacity at the end of 2017 was 47780 million m^2 (i.e. 334.5 GW_{th}) (see Fig. 1) [11]. Therefore, China accounted for 71% of total global capacity [8]. By 2017, China's solar thermal application area reached 3.43 billion m^2. Currently solar energy heat utilization is mainly used for domestic hot water supply, which account for 40.7% of the total. Among them, residential projects still account for 63% of the first, commercial engineering (hospitals, Hotels, schools, nursing homes, etc.) accounted for 28%, and industrial and agricultural and other fields only accounted for 9%.

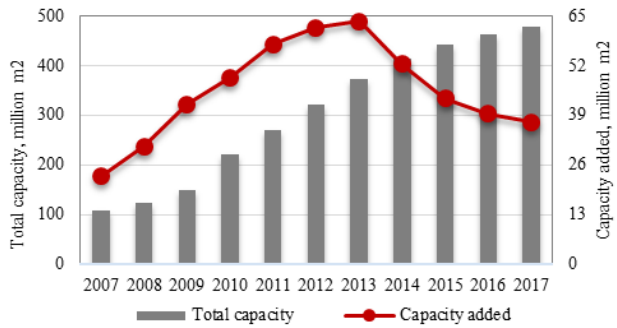

Fig 1 Solar water heating collectors in China, 2007-2017 [11].

The literature review showed that most of the field trials are done in short time frame that does not allow to properly investigate the SDHW system performance under a variety of occupancy and weather conditions. In order to well understand the real-life performance of SDHW, an online monitoring platform is needed. In this paper, continuous real-life SDHW system data over one year were collected for dynamic thermal performance analysis. The results can be used to optimize the household's hot water supply system and in- crease efficiency in its use. Recommendation to improve the SDHW system performance and reduce greenhouse gas emissions was given finally.

2. METHODOLOGY

2.1 Solar domestic hot water systems

The project is located in Pudong New District of Shanghai. Shanghai is the hot summer and cold winter regions. Its main climate features are: four distinct seasons, full sunshine, short spring and autumn, long winter and summer, annual average temperature around 16 °C, annual average sunshine hours of 5.5 hours, belonging to the general area of solar energy resources. According to the typical meteorological year parameters, the average temperature in winter in Shanghai (from December to March) is around 6 °C. And the amount of solar radiation is relatively weak compared to summer. The average temperature in summer (June to September) is around 26°C, which is with good solar radiation. In the transition season (spring and autumn), the solar radiation amount was also sufficient for a total of 4 months. The monthly total solar radiation and the outdoor average dry bulb temperature of Shanghai are shown in Fig. 2.

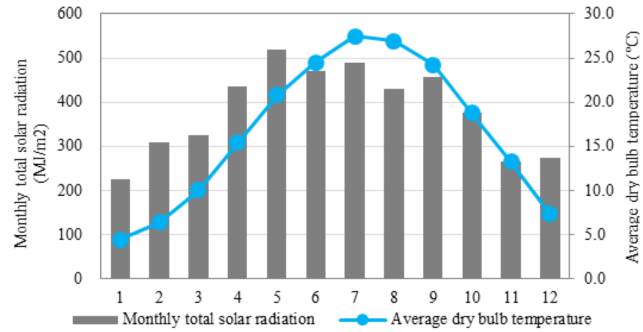

Fig 2 Monthly total solar radiation and average dry bulb temperature in Shanghai.

There are 50 dormitories in this university, and each dormitory install a SDHW system for students to take a bath. A male dormitory was selected as the case building in this study. This dormitory has six floors and around 430 students. There is a bathroom at each end of each floor. Each bathroom has 3 faucets and a total of 36 faucets. The water supply time is from 15:00 to 22:45 every day, and the water supply temperature is 50~52°C. The SDHW system uses the glass evacuated solar tube collector, with an average collector area of 260 m^2, which is placed on the roof. The second floor podium is equipped with a hot water storage tank and a constant temperature heating water tank. The hot water storage tank has a volume of 12 m^3 and is assisted by three air source heat pumps with a heat capacity of 36 kW. The constant temperature heating water tank has a volume of 6.75 m^3 and is heated by a 9 kW electric heating.

2.2 Experimental measurement

All SDHW systems were equipped with data logging system and remotely monitored with online data. The monitoring system of Building No. 27 is shown in Fig. 3. The parameters for real-time monitoring mainly include solar radiation, outdoor air temperature, water temperature, water flow, water level, start and stop of the pump, start and stop of the auxiliary heat source, power consumption of water pump and auxiliary heat source, etc. The sampling interval is 2 minutes.

2.3 Evaluation method

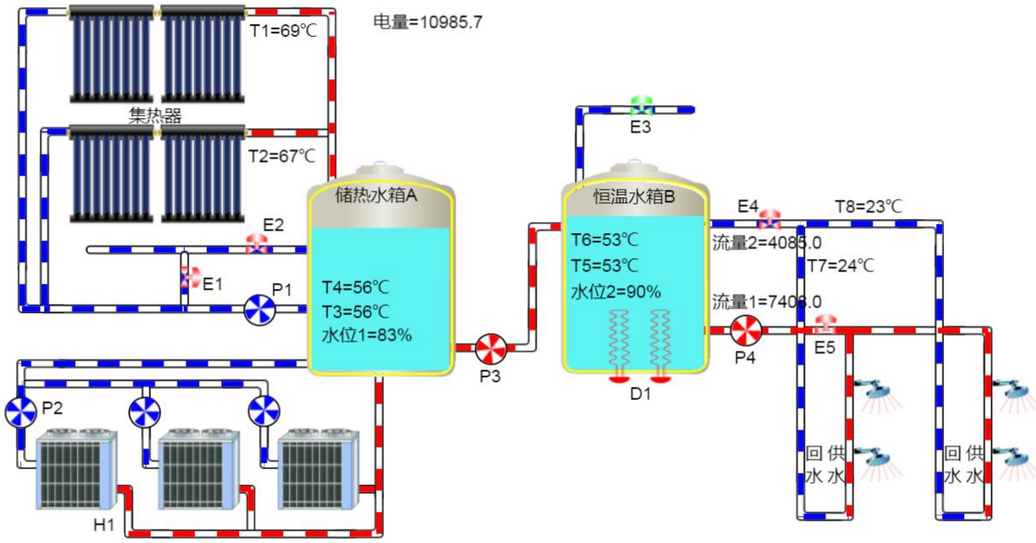

Fig 3 Schematic diagram of SDHW system monitoring platform (the figure showed the data of 11:13:41 on October 11, 2018).

Based on monitoring data for one year (October 2017 to September 2018), thermal performance analysis and economic analysis of SDHW systems were presented in this paper, including four thermal performance indicators and one economic indicator.

（1）Solar contribution ratio——This indicator considers the extent to which the effective heat gain of solar energy in the system contributes to the actual needs of users.

（2）Solar effective utilization ratio——This indicator considers the efficiency of the solar energy utilization of the system, that is, the effective heat gain of the solar energy (the heat that the user can actually use) accounts for the proportion of the heat gain of the solar collecting system in the SDHW system.

（3）Unit hot water heat loss——This index considers the heat dissipation of the system, that is, the heat dissipation of the system piping and the water tank to the heat demand of the user, and it more intuitively shows the relationship between loss and gain.

（4）Unit hot water conventional energy consumption——In addition to the above three indicators, the most direct reflection of the energy-saving effect of the SDHW system is the amount of conventional energy actually consumed per ton of hot water. For different hot water systems, this indicator can be used as a common index for horizontal comparison, so as to directly obtain the energy consumption performance of different types of hot water systems.

（5）Unit hot water cost——This indicator shows the cost of per ton of hot water over the lifetime, which directly reflects the economic performance of the system.

3. RESULTS AND DISCUSSION

3.1 Thermal performance analysis

The annual total energy consumption and system thermal performance indicator of the SDHW system of the dormitory are shown in Table 1. The solar contribution ratio of the system is 0.71, according to Evaluation Standards for Application of Renewable Energy in Buildings GB/T50801-2013, the system can be divided into level 1 (the highest level). The system's solar effective utilization ratio (0.56) is also high, while the system’s unit hot water heat loss and tons of unit hot water conventional energy consumption are low. Therefore, the overall thermal performance of the system is generally good. On the one hand, it’s because the system design is reasonable, on the other hand, it is due to the particularity of water usage in dormitory. The system provides regular water supply to effectively avoid large heat loss caused by round-the-clock circulation. In addition, the water points in the dormitory are concentrated, the water supply circulation pipeline is simple, and the loss of pipeline transmission and distribution is relatively small.

Fig. 4. shows the monthly dynamics of the four thermal performance indicators of the SDHW system. The solar contribution ratio for all other months except February was higher than 0.5. In the winter (November to February), the solar contribution ratio is slightly lower than other months, especially in February, it is approximately zero. This is because during the winter vacation in February, there are still a few students in school that cannot turn off the SDHW system. The water consumption in February (13 tons) is only 5% of the

Table 1 Annual energy consumptions and thermal performance of SDHW system.

Heat gain of the solar collecting system, GJ	Energy consumption by the auxiliary energy supply, GJ	Heat dissipation of the system, GJ	Heat consumption by the end users, GJ	Solar contribution ratio	Solar effective utilization ratio	Unit hot water heat loss	Unit hot water conventional energy consumption, kWh/t
571	132	251	454	0.71	0.56	0.55	3.26

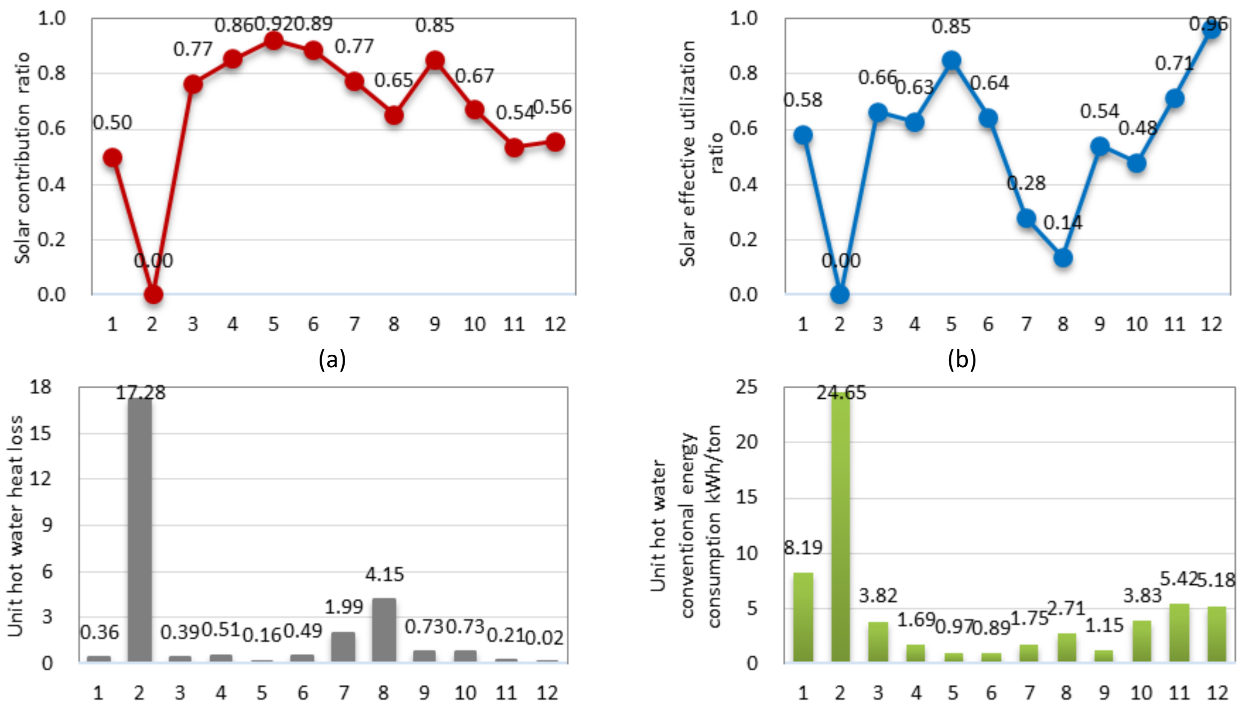

Fig 4 Monthly thermal performance indicator of SDHW system.

annual average water consumption, and the students are not guaranteed to use water during the effective collection period of the system, which account for the collected heat is wasted a lot. In addition, in order to maintain the normal operation of the system, it is still necessary to provide auxiliary energy. Therefore, in February, the solar contribution ratio was zero. During the summer vacation in August, water consumption also decreased significantly, maintaining 40% of the average monthly water consumption for the whole year. As a result, for the student dormitory system, the impact of changes in water consumption due to winter and summer vacations on solar contribution ratio is significantly greater than seasonal factors.

Due to the summer and winter vacations, the solar effective utilization ratio of the system decreased sharply in February, July and August. And the solar effective utilization ratio is higher in November and December, which means that a higher proportion of solar heat collected is actually utilized is really higher, that is, a smaller proportion of system heat dissipation. On the one hand, this may be related to the operation strategy of the system, because the cycle time of the system is relatively short; on the other hand, Shanghai has just entered winter in December, so its heat loss is relatively small compared with January to march, so the solar effective utilization ratio is relatively high. However, the heat collected in summer is greater than the heat used, and some unused heat collection is converted into heat dissipation. Therefore, the proportion of solar energy effective utilization is lower than that in November and December.

3.2 Economic analysis

This section conducts an economic analysis of the system with unit hot water cost in the whole life cycle. According to the literature [12], the life of the SDHW system is determined to be 13 years. The initial investment in the system and the energy prices of residents in Shanghai are shown in Table 2. The

Table 2 Initial investment and energy prices.

Auxiliary energy type	Initial investment	Residential electricity price, yuan/kWh	Natural gas price, yuan/m^3
Air source heat pump	Vacuum tube collector: 1000 yuan/ m^2 Heat pump： 20000 yuan/uint	0.636	3.00

Table 3 Annual Economic indicator of SDHW system.

Unit hot water cost, yuan/ ton	Unit hot water initial investment, yuan/ ton	Unit hot water energy cost, yuan/ ton
10.63	7.06	2.07

calculation results of the annual economic evaluation indicator of the system are shown in Table 3.

The SDHW system in the student dormitory has a significant advantage in unit hot water energy cost. Although the air source heat pump increased the initial investment of the system, unit hot water conventional energy consumption is low due to the good operation of the system and good thermal performance. Moreover, the application of heat pump significantly reduces the power consumption of the system and reduces the energy cost of the system. Therefore, as an important part of SDHW system design, the choice of auxiliary energy will affect the economic performance of the system.

4. CONCLUSIONS

In this paper, the SDHW system of a student dormitory in a university in Shanghai is investigated and monitored. Based on the operating data for one year, the thermal performance of the system and the economics in the whole life cycle are analyzed. The results show that the thermal performance and economic performance of SDHW system in student dormitory are far better than that in residential SDHW system. The water demand of the centralized bathroom in student dormitory is relatively concentrated in time and space, which is very beneficial to the application of SDHW system.

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REFERENCE

[1] Rosenfeld AH. Energy efficient buildings in a warming world. In: Tester JW, Wood DO, Ferrari NA, editors. Energy and the environment in the 21st Century; 1990, p. 459–73.

[2] Geller H, Harrington P, Rosenfeld AH, Tanishima S, Unander F. Polices for increasing energy efficiency: Thirty years of experience in OECD countries. Energy Policy 2006; 34:556-73.

[3] Prindle B, Eldridge M, Eckhardt M, Frederick A. The twin pillars of sustainable energy: synergies between energy efficiency and renewable energy technology and policy. ACEEE; 2007.

[4] Settino J, Sant T, Micallef C, Farrugia M, Spiteri Staines C, Licari J, et al. Overview of solar technologies for electricity, heating and cooling production. Renewable and Sustainable Energy Reviews 2018; 90:892–909.

[5] Duffie JA, Beckman WA. Solar Engineering of Thermal Processes. 2th ed. John Wiley & Sons, INC; 1991.

[6] Ogueke NV, Anyanwu EE, Ekechukwu OV. A review of solar water heating systems. Journal of Renewable & Sustainable Energy 2009; 1, 043106.

[7] Kong W, Wang Z, Li X, Yuan G, Fan J, Perers B, et al. Test method for evaluating and predicting thermal performance of thermosyphon solar domestic hot water system. Applied Thermal Engineering 2019; 146:12-20.

[8] REN21. RENEWABLES 2018 GLOBAL STATUS REPORT–SOLAR THERMAL HEATING AND COOLING. 2018. REN21 website, http://www.ren21.net/wp-content/uploads/2018/06/17-8652_GSR2018_FullReport_web_final_.pdf [accessed 9.2.19].

[9] Li K, He F. Analysis on mainland China's solar energy distribution and potential to utilize solar energy as an alternative energy source. Progress in Geography 2010; 29(9): 1049-54. (In Chinese)

[10] China National Engineering Research Center for Human Settlements. Integration design for solar water heating system in dwelling. Beijing: China Architecture and Building Press; 2006. (In Chinese)

[11] China Solar Industry Information. China solar thermal utilization industry operating status report; 2018. http://www.cnste.org/html/zixun/2019/0314/4629.html. (In Chinese)

[12] Li W, Song G, Beresford M, Ma B. China's transition to green energy systems: The economics of home solar

water heaters and their popularization in Dezhou city. Energy Policy 2011; 39(10):5909-19.