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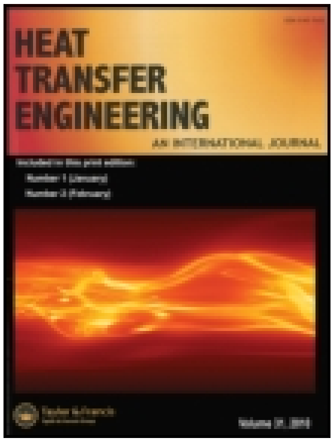

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Redesign of a Water Heating System Using Evacuated Tube Solar Collectors: TRNSYS Simulation and Techno-Economic Evaluation

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In this paper, a solar water heating system (SWHS) is designed to substitute for a gas geyser system (GGS). First, a mathematical model for the SWHS is built according to the thermodynamic and hydrodynamic theories; then the transient performances of the system are analyzed using the TRNSYS (Transient System Simulation) program; and finally, the techno-economics of the SWHS are evaluated. The annually mean solar fraction of the SWHS is 0.56. TRNSYS simulation results show that the water temperatures at the solar collector outlet and in the tanks are much higher in summer than in winter because of the solar radiation and ambient temperature effects, and auxiliary heat is frequently required in winter. Comparing with the original GGS, the SWHS is cost-effective and its payback period is 7.4 years. The redesign work is of high value for northwest China, considering the abundant solar radiation, the underdeveloping economics, and the environmental conservation in such regions.

INTRODUCTION

In recent years, China has faced a great challenge to meet an immense energy demand under more and more stringent environmental constraints. China's total energy consumption in 2009 is up to 3055 million tons of standard coal equivalent, and the fossil fuel-based energy structure has released extensive emissions of local air pollutants such as sulfur dioxide (SO_2), nitrous oxide (NO_x), and particulate matter (PM) [1]. Not only would the fossil fuels be exhausted in the near future, but it is also difficult for them to satisfy the requirements of China's sustainable development. It is urgent to develop technologies utilizing renewable energy resources to solve conflicts between the environmental sustainability and fossil fuel shortage and pollution in China. Solar energy is an abundant, low-cost, clean, and endless energy source free of greenhouse gases emissions. Redesign of fossil fuel systems by importing solar energy is thus of high value for areas with abundant solar radiation and high energy consumption. Like solar energy, hot water consumption has the characteristics of high quantity but low quality. Hot water supply in hotels is usually powered by fossil fuels, such as natural gas and coal. Redesign of water heating systems in hotels utilizing solar energy is thus of high significance to China.

The solar water heating system (SWHS) has been extensively studied. Bliss established mathematical models for some kinds of solar collectors [2]. Abdel-Malek and Chu [3] performed an evaluation of a SWHS and analyzed the percentage of energy contributed by the sun to the total required load by users. Tiwari et al. [4] developed a mathematical model for a SWHS and validated their model by a series of experiments. Also, Tiwari et al. [5] installed two large SWHSs and studied their performances under the thermosyphon mode between the collectors and storage tanks. Layek [6] carried out an optimum design for SWHSs in different locations. Recently, Michaelides and Eleftheriou [7] made an experimental investigation of the performance boundaries of a SWHS, and analyzed the influences of solar radiation and water flow rate on the performances. Some

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scholars [8–10] simulated the performances and optimized the parameters of SWHSs by the TRNSYS (Transient System Simulation) program. Hobbi and Siddiqui [8] simulated an indirect forced circulation SWHS for domestic hot water requirements of a single-family residential unit in Montreal, Canada. Ayompe et al. [9] proposed a TRNSYS model for forced-circulation SWHSs used in temperate climates. Odeh and Behnia [10] carried out a long-term performance modeling of the PV/thermal combined system for both power generation and hot water supply using TRNSYS. On the other hand, the techno-economic evaluation of SWHSs has also been frequently reported from different countries [11–15]. Mijovic [11] made an economic analysis on the SWHS for Yugoslavia, in which he covered the factors contributing to the cost-effectiveness of solar water heating. Diakoulaki et al. [12] presented a cost–benefit analysis for evaluating the SWHS in comparison with the competitive conventional technologies in Greece. The techno-economic evaluation of SWHSs in developing countries such as Jordanian and India were also reported by Kablan [13] and Chandrasekar and Kandpal [14]. Michels et al. [15] analyzed the economic return and quantified the reduction in the emission of pollutants with low-cost solar collectors used as a partial substitute for a fuel oil boiler in Brazil.

Much consideration has been focused on the design, optimization, and techno-economic evaluation of a new system. However, few research studies have been devoted to those places where water heating systems already existed. Northwest China is an area with the annual total solar radiation over 5500 MJ/m^2 and annual sunshine duration over 3000 hours. Moreover, in winter months, natural gas shortage has been frequently reported in northwestern regions [16]. Considering this background, this paper aims to design a SWHS to substitute for the original gas geyser system (GGS) of a hotel in Xi'an, China, and the main tasks in this work are summarized as:

1. To redesign the original GGS by employing evacuated tube solar collectors.
2. To analyze the performances of the designed SWHS using TRNSYS program.
3. To evaluate the techno-economics of the designed SWHS.

SYSTEM MODEL

There are some requirements for the SWHS in a hotel: (1) The system should maintain 24 hours of hot water supply in one day and endure high hot water consumption at night; (2) an auxiliary heater should exist for both cloudy and rainy days; (3) solar energy should be the main and prior energy source in the SWHS; and (4) the investment of the SWHS should be cost-effective compared to the original GGS. To fulfill the preceding requirements, some solutions are proposed:

1. As the ambient temperature in Xi'an might be lower than the freezing point, forced circulation and direct heating are determined as the operation strategy.
2. Evacuated tube solar collectors are chosen as the main energy module, because of their high efficiency, low cost, antifreezing property, and high popularity in China.
3. Hot water tanks are used for energy storage and to provide temperature-stable hot water.
4. Differential temperature controllers are used to control water circulation flow rates.
5. The original gas boiler is maintained as the auxiliary heater. Moreover, the original cold and hot water supply pumps and the hot water supply tank are all reserved in the designed SWHS.

The main components of the original GGS and the SWHS are described in Figure 1. As shown in Figure 1, the municipal

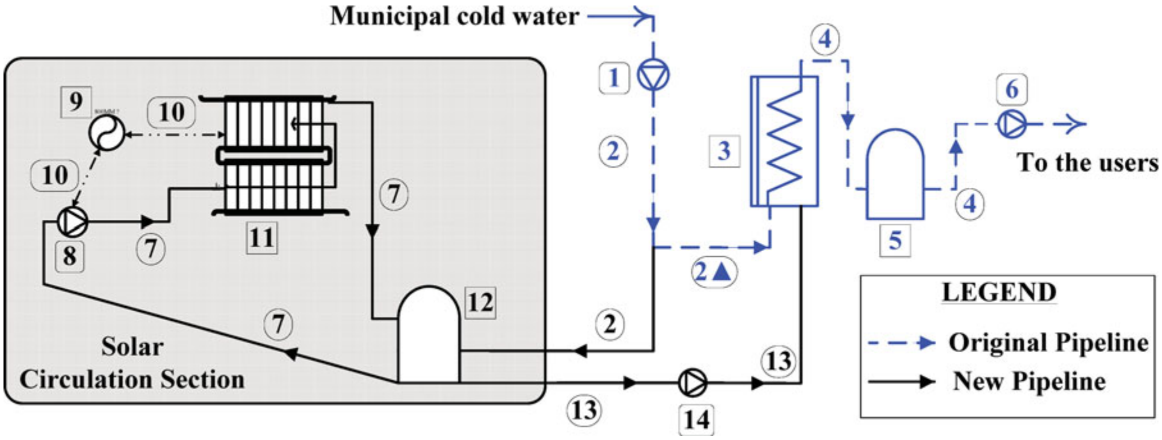


Figure 1 Schematic of the original GGS and the SWHS. (In the SWHS, water pipe 2▲ is used only under emergency or equipment maintenance situations.) 1, Cold water pump; 2, cold water pipe; 3, gas boiler/auxiliary heater; 4, hot water supply pipe; 5, hot water supply tank (supply tank); 6, hot water supply pump; 7, water pipes in circulation sections (circulation pipe); 8, circulation pump; 9, temperature controller; 10, signal line; 11, evacuated tube solar collectors; 12, water tank in circulation section (circulation tank); 13, pipelines in auxiliary heat section (auxiliary pipe); 14, auxiliary heater pump (auxiliary pump). (Color figure available online.)

cold water fills the circulation tank via the cold water pump. The cold water then enters into the solar circulation section, in which the water is circularly pumped between the circulation tank and the solar collectors. The on/off temperature differential controller is used to control the circulation flow rate. The water with high temperature is drawn out from the circulation section by the auxiliary pump and enters into the auxiliary heater in which the water is heated to the desired temperature. Finally, the hot water is stored in the supply tank, waiting for the users' consumption. Note that the cold-water pipelines of the original GGS are reserved for the consideration of emergency and equipment maintenance.

Thermodynamic Analysis

The heat balance in the solar collectors is given as follows:

$$Mc_p\left(\frac{\partial T_w}{\partial \tau}\right) - \frac{\partial Q_{sun}}{\partial \tau} = 0 \tag{1}$$

where Q_{sun} is the heat absorbed by the water from the sun and could be expressed as

$$Q_{sun} = \eta_{col}(1 - \eta_L)A_{col}J_T \tag{2}$$

where J_T is the annually average daily total solar irradiation and η_{col} is the solar collector efficiency. They could be calculated by the following equations:

$$J_T = \bar{H}_t \times Time \tag{3}$$

$$\eta_{col} = a - bT^* - c\bar{H}_t T^{*2} \tag{4}$$

where $\bar{H}_t$ is the annually average daily total solar radiation on the sloped surface and is calculated as [17]:

$$\bar{H}_t = (\bar{H}_{hor} - \bar{H}_d)R_b + \frac{1}{2}\bar{H}_d(1 + \cos\beta) + \frac{1}{2}ref \cdot \bar{H}_{hor}(1 - \cos\beta) \tag{5}$$

By integrating Eq. (1), the area of solar collectors needed for the hot water supply is

$$A_{col} = \frac{Mc_p(T_{end} - T_c)f}{J_T\eta_{col}(1 - \eta_L)} \tag{6}$$

where a solar fraction f appears in the numerator for the consideration of cloudy and rainy days [18].

Considering the deviation of the azimuth angle and the shadow of the surrounding buildings, a correction of A_{col} is required:

$$A_{cor} = \frac{A_{col}}{R_{cor}} \tag{7}$$

The power capacity of the auxiliary heater P_{aux} is set as the total heat required by the system P_{tot}, which could be calculated by the following equation:

$$P_{aux} = P_{tot} = \frac{k_h Mc_p(T_{end} - T_c)}{24 \times 3600} \tag{8}$$

Hydrodynamic Analysis

The pump flow rate in the circulation section q_{cir} is

$$q_{cir} = B_1 \times A_{cor} \tag{9}$$

and the pump flow rate of the auxiliary heater q_{aux} is

$$q_{aux} = \frac{P_{loss}}{c_p\Delta T_{CS}\rho} \tag{10}$$

where $\Delta T_{CS} = 5°\text{C}$, and $P_{loss} = 5\% \times P_{tot}$ [19].

The equivalent diameter of the pipes d_j could be calculated using the following equation [20]:

$$d_j = \sqrt{\frac{4q_j}{\pi v}} \tag{11}$$

The volume of the circulation tank V_{cir} is [20]

$$V_{cir} = B_2 \times A_{cor} \tag{12}$$

The pressure head of the pumps H_p is consumed by the pipeline hydraulic loss H_{hyd} and the pressure loss in the solar collector H_{col}:

$$H_P = H_{hyd} + H_{col} \tag{13}$$

where

$$H_{hyd} = \frac{L_{th}P_0}{\rho g} \tag{14}$$

$$H_{col} = P_{0,col} \times A_{col} \tag{15}$$

The equation for estimating the frictional head loss along per unit water pipeline length P_0 is [21]

$$P_0 = 105C_h^{-1.85}d_j^{-4.87}q_j^{1.85} \tag{16}$$

System Control and Solar Fraction

The signal of the temperature differential controller is

$$Sgn = \begin{cases} 0 & \Delta T_{OI} < \Delta T_U = 5°\text{C} \quad or \quad \Delta T_{OI} < T_{cut} = 0°\text{C} \\ 1 & \Delta T_{OI} > \Delta T_L = 20°\text{C} \quad or \quad \Delta T_{OI} > T_{cut} = 95°\text{C} \end{cases} \tag{17}$$

where ΔT_{OI} is the water temperature difference between the solar collector outlet and inlet, and ΔT_U and ΔT_L are the upper and lower cutoff temperature differences. The operating principle of the temperature differential collector could be described as: If the temperature difference between the collector inlet and outlet is smaller than 5°C, the water in the collector is reserved for insolation, whereas if the temperature difference is larger than 20°C, the water in the collector is forced to circle. Note that the default state of the signal is 1, and only when the ΔT_U or ΔT_L occurs is the signal then changed correspondingly. In addition, a special cutoff temperature T_{cut} is set to avoid the water freezing or boiling.

The solar fraction of the SWHS is the amount of energy provided by the solar technology divided by the total energy load, which could be expressed as:

$$f = \frac{Q_{load} - Q_{aux}}{Q_{load}} = \frac{\sum_{i=1}^{365} (P_{load,i} - P_{aux,i})}{\sum_{i=1}^{365} P_{load,i}} \tag{18}$$

where Q_{load} is the total energy to meet the water heating requirements, Q_{aux} is the auxiliary energy supplied to the system to support the portion of the total load that is not provide by the solar energy, and $P_{load,i}$ and $P_{aux,i}$ are the daily total energy load and auxiliary heat in the ith day.

THE SWHS OF A HOTEL IN XI'AN

Xi'an (34°18′N, 108°56′E) is located in the geographic centre of China. Its annual average ambient temperature is 13.3°C, daily average total radiation on the horizontal is 11.77 MJ/m^2, and monthly average sunshine duration is 142.59 hours. We choose one four-star hotel in Xi'an, the Nanyang Hotel, as the object for study. A GGS was originally installed to supply hot water for 200 standard rooms, 15 multiple rooms, and one public washing room. The daily total hot water consumption is 35 tonnes. A planar graph of Nanyang Hotel is shown in Figure 2. Only the shaded sections A and E could be used to place the solar collectors. Section A has a configuration size of 61.0 m × 15.0 m and section E has a size of 43.2 m × 14.4 m.

Some parameters and design results of the original GGS and the SWHS are shown in Table 1. The water in the hot supply tank is desired to be heated up to 60°C in the auxiliary heater. From Table 1, it is found that the practical solar collector area is smaller than the theoretically calculated result, owing to the total area limitation in sections A and E of the hotel. Note that the cold-water pump and the cold-water pipe are from the municipal water net, not needing special design, and thus no parameters about them are shown.

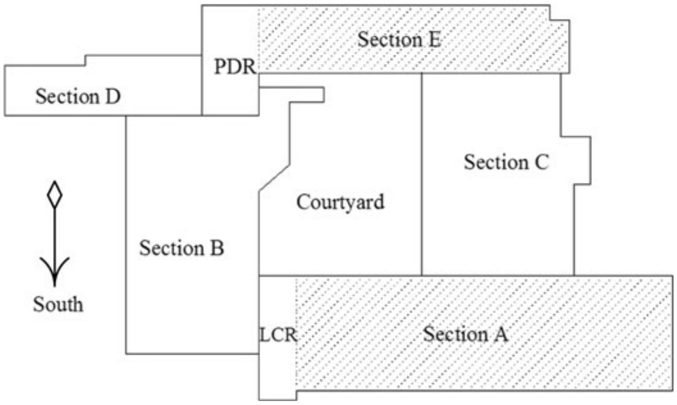


Figure 2 Planar graph of Nanyang Hotel (PDR is the power distribution room and LCR is the lift control room).

Table 1 Parameters and designed results of the original GGS and the SWHS

Component	Parameter [unit]	Value
Original GGS	Hot water supply tank volume [m^3]	15
	Pumping head of hot water supply pump [m]	40
	Diameter of hot water supply pipe [mm]	100
Solar collectors	Collector compensation area ratio [—]	0.92
	Hourly variation coefficient [—]	4.83
	Annually average collector efficiency [%]	47.3
	Flow rate of solar collectors per unit area [L/(m^{2}s)]	0.02
	Hot water productivity per unit collector area [m^3/m^2]	0.05
	Pressure drop in solar collectors [kPa/m^2]	0.5
	Solar collector tilted angle [°]	50
	Theoretically required collector area [m^2]	880.35
	Practical total solar collector area [m^2]	688.64
	Practical solar collector area in section A [m^2]	408.88
	Practical solar collector area in section E [m^2]	279.76
Pumps	Hazen–Williams coefficient [—]	130
	Average pipeline length [m]	90
	Pumping head of circulation pump in section A [m]	25
	Pumping head of circulation pump in section E [m]	20
	Pumping head of auxiliary pump [m]	15
	Water circulation flow rate in section A [L/s]	8.18
	Water circulation flow rate in section E [L/s]	5.60
	Auxiliary heat pump flow rates [L/s]	5.65
Tanks	Loss coefficient [—]	0.25
	Tank volume in section A [m^3]	25
	Tank volume in section E [m^3]	15
Auxiliary heater	Efficiency [—]	0.85
	Power capacity [kW]	500
	Water flow rate [L/s]	5.65
Pipelines	Loss coefficient [—]	0.25
	Auxiliary pipe diameter [mm]	90
	Pipe diameter in section A [mm]	100
	Pipe diameter in section E [mm]	80

TRNSYS SIMULATION

A TRNSYS project is established to simulate the transient performances of the designed SWHS. The TRNSYS information flow diagram is shown in Figure 3. The parameters in Table 1 are set as the "inputs" or "parameters" of the corresponding TRNSYS "type." The typical meteorological year (TMY) data are supplied by TRNSYS type 109. The dashed lines represent the control signals and the solid lines represent the water flow paths. The parameters in the dashed-line boxes between types are the transferred information, in which T stands for the water temperature, T_a stands for the ambient temperature, m stands for the mass flow rate, and numbers are the control signals. Figure 4 presents daily water consumption in the hotel. There are two hot-water consumption peaks, at 9:00 a.m. and 7:00 p.m. From 1:00 a.m. to 6:00 a.m. there is no hot-water consumption.

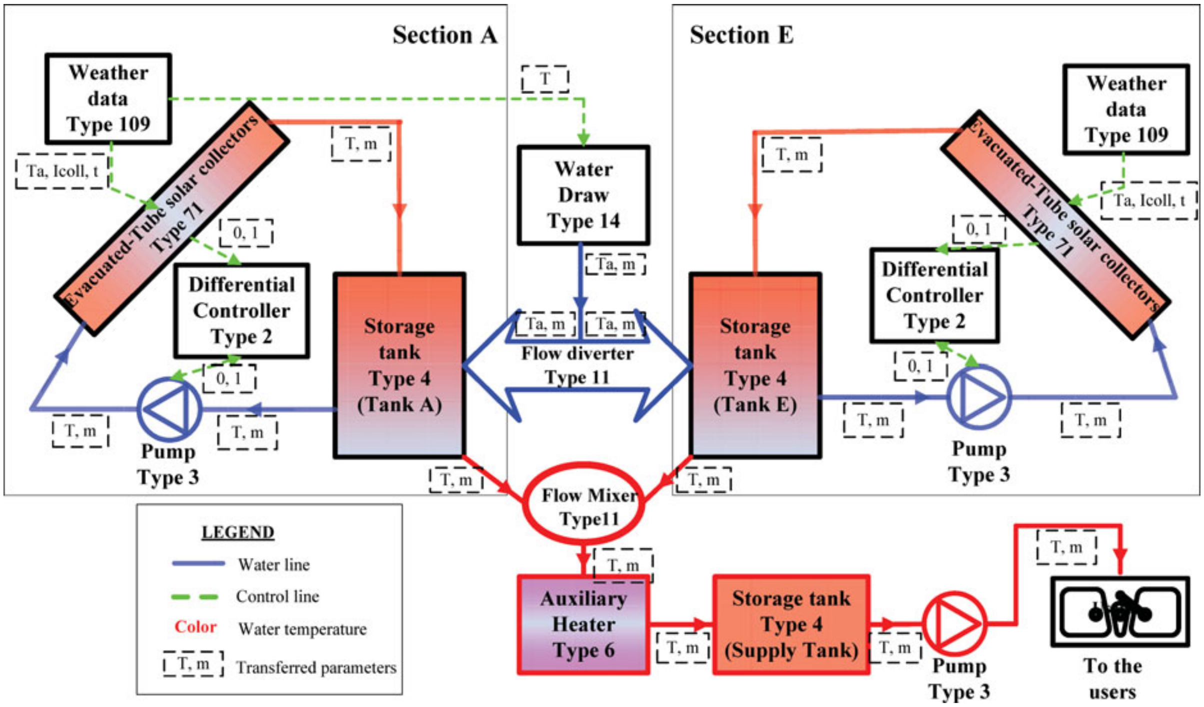


Figure 3 TRNSYS information flow diagram of the designed SWHS. (Color figure available online.)

RESULTS AND DISCUSSIONS

Water Temperatures

Figure 5 shows the daily total solar radiation, ambient temperature, and water temperatures at the outlet of solar collectors in sections A and E during 1 week each in spring and in summer. The week in spring is March 20 to 26 and in summer it is June 20 to 26. The spring equinox and summer solstice days are included in these two weeks, respectively. It is found from the figure that:

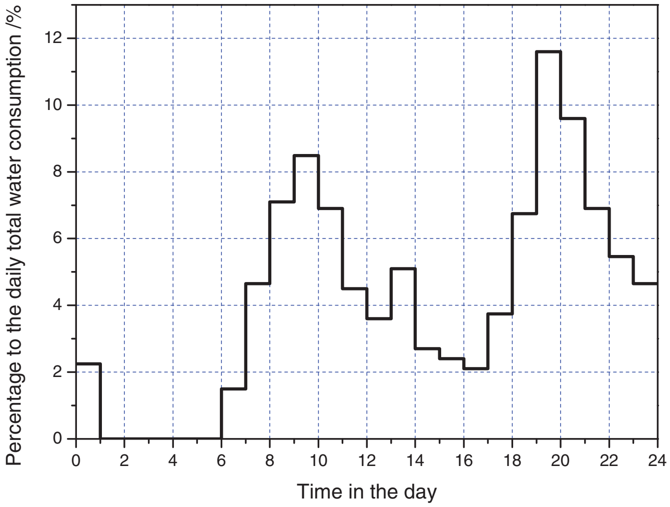
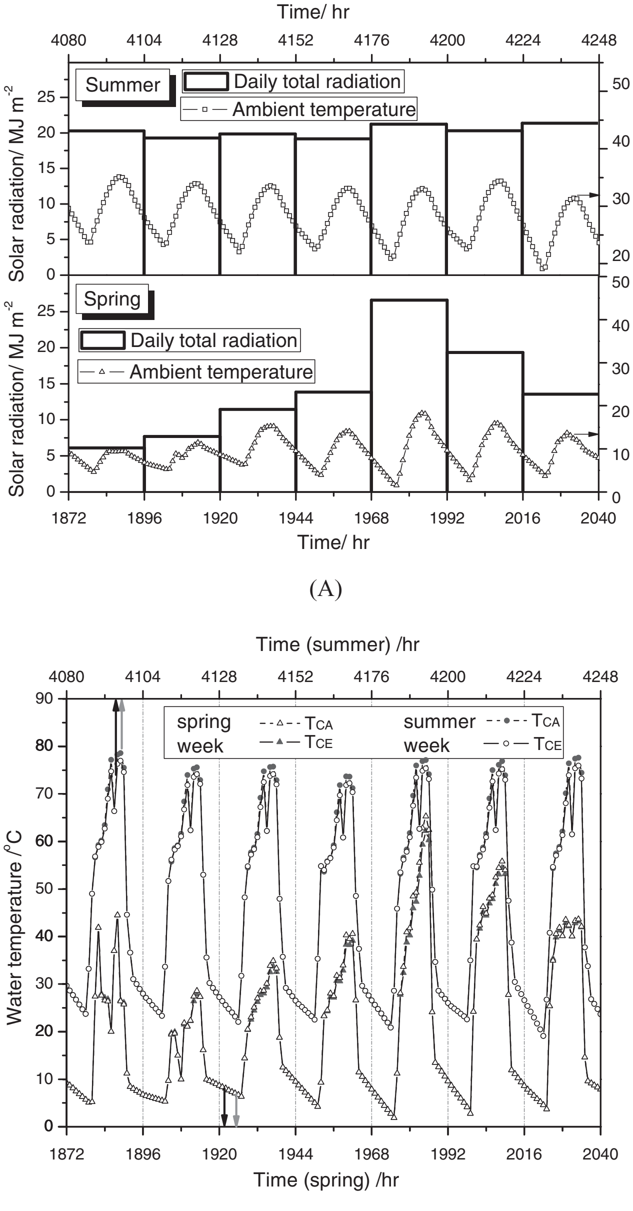


Figure 4 Normalized daily hot water consumption in the hotel. (Color figure available online.)

1. The ambient temperature ranges from 19.1 to 35.1°C in the summer week and from 1.5 to 18.3°C in the spring week. The total solar radiation in the summer week is more stable than that in the spring week. Moreover, the daily repeatability of ambient temperatures in the summer week is more significant than that in the spring week.
2. The variation of water temperatures at the solar collector outlet is periodic, and there are 24 hours in one cycle. In each cycle, from midnight to 6:00 a.m., the water temperature decreases gradually. Then after sunrise, water in the collectors is heated and circulated, and the water becomes hot gradually. During the daytime, the hot water is consumed and cold water is pumped in as well as heated up uninterruptedly. Water temperatures thus vary with a certain relationship to the solar radiation and water consumption. Finally, due to the sunset, the water temperature drops steadily from 9:00 p.m. to 6:00 a.m. of the next day. The water temperature at the collector outlet in section A is slightly larger than that in section E by 2°C due to the larger solar collector area.
3. In the summer week, the water temperature at the collector outlet ranges from 20.5 to 76.9°C, and the variations between days are similar. During the daytime from 6:00 a.m. to 9:00 p.m., the water temperatures at the collector outlet of sections A and E both rise steadily from 6:00 a.m. to 2:00 p.m. first, then drop between 2:00 p.m. and 5:00 p.m., and finally decline sharply from 5:00 p.m. to 9:00 p.m. The water temperature drop at 3:00 p.m. is a complex result of the large consumption of hot water at 9:00 a.m. and the increasing solar radiation from 9:00 a.m. to 2:00 p.m. Owing to the buffering effect of the hot water tanks and the increasing solar



(A)

(B)

Figure 5 (A) Daily total solar radiation and ambient temperature during one week in spring and summer week. (B) Water temperatures at the outlet of solar collectors in section A (T_{CA}) and section E (T_{CE}) during one week in spring and summer.

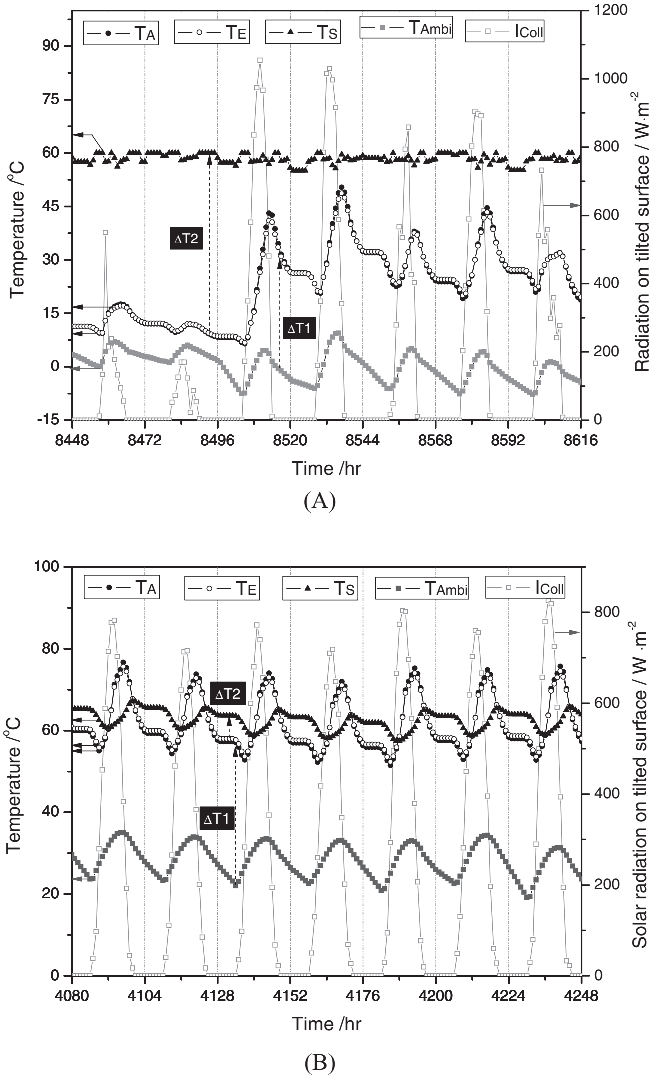
radiation, the influence of the peak water consumption on the water temperature is postponed from 9:00 a.m. to 3:00 p.m. In addition, the other peak water consumption at 7:00 p.m. causes a rapid water temperature decrease from 7:00 p.m. to 9:00 p.m.

4. In the spring week, the water temperature at the collector outlet ranges from 1.9 to 65.3°C. However, the water temperature variations between days in the spring week are not similar, due to the significantly unstable solar radiation. The already-mentioned temperature tendencies during the daytime from 7:00 a.m. to 8:00 p.m. also appear in some days of the spring week. But the temperature drop time in the spring week is brought forward and extended, which lasts from 10:00 a.m. to 4:00 p.m. The reason for the time brought forward is that the hot water temperature in spring is lower than that in summer. As the users consume a large amount of hot water at 9:00 a.m., a large quantity of cold water is pumped into the circulation tank. The water in summer is heated up to higher than 70°C, whereas the water in spring can only be heated up to higher than 40°C. In addition, the solar radiation and the ambient temperature in the spring week are weaker or lower than those in the summer week. Consequently, the influence of incoming cold water on the hot water is thus more significant in the spring week than that in the summer week, which finally causes the bringing ahead and expansion of the temperature drop. From March 22 to 25, as the ambient temperature during the daytime is relatively higher and solar radiation is also stronger, no obvious temperature drop but some small temperature fluctuations could be observed during the daytime.

In Figures 6A and 6B, we present the water temperatures in circulation and supply tanks, the ambient temperature, and the total solar radiation on sloped collector surfaces. ΔT_1 denotes the temperature rise from the ambient to the water temperature in circulation tanks, and ΔT_2 denotes the temperature rise from the circulation tanks to the supply tank. The week in summer is June 20 to 26 and in winter is December 19 to 15. The summer and the winter solstice days are included in these two weeks, respectively. With the figure, it is observed that:

1. In the winter week, the ambient temperature ranges from –7.5 to 9.4°C. The water temperature in the circulation tank A is similar to that in the circulation tank E, with the maximum difference smaller than 2°C. The water temperatures range from 6.4 to 50.4°C in the circulation tank and from 55.1 to 60.0°C in the supply tank, respectively. The highest solar radiation in the winter week is 1054.2 W/m^2.
2. In the summer week, the water temperature in the circulation tank A is also similar to that in the circulation tank E, with the difference no more than 2°C. The water temperatures range from 51.5 to 76.7°C in the circulation tank and from 57.4 to 65.9°C in the supply tank, respectively. The highest solar radiation in this week is 825.9 W/m^2. Besides, the variations of water temperatures in the circulation and supply tanks are periodic in the summer week, due to the periodical daily ambient temperature and solar radiation.

In order to guarantee the hot-water supply in winter, a solar collector installed at a large tilted angle is required for employing more solar radiation. The solar radiation and ambient temperature both have positive effects on the water temperatures in circulation tanks A and E: The stronger solar radiation or higher ambient temperatures would cause higher water temperatures in the tanks. This is a general phenomenon in SWHSs. Ayompe et al. [9] reported a similar tendency among the



(A)

(B)

Figure 6 Tank water temperatures in section A (T_A) and section E (T_E), water temperatures in the hot water supply tank (T_S), ambient temperature (T_{Ambi}), and the solar radiation on tilted surfaces (I_{Coll}): (A) during one week in winter, and (B) during one week in summer.

ambient temperature, solar radiation, and collector outlet temperature for a flat plate collector system. Also, the positive effects are demonstrated in figures by Tsilingiris [22] and Bojic et al. [23].

In the SWHS, solar energy and the auxiliary energy are the energy source. The amounts of these two energy sources are relevant to ΔT_1 and ΔT_2. Both ΔT_1 and ΔT_2 are significantly influenced by the solar radiation and the ambient temperature. The variations of ΔT_1 and ΔT_2 indicate the delivered energy in the SWHS, which are shown in Figure 7.

Auxiliary Heat and Solar Fraction

Figure 7 shows the energy absorbed daily by the collectors and the energy delivered by the auxiliary heater throughout the year. From this figure, it can be found that:

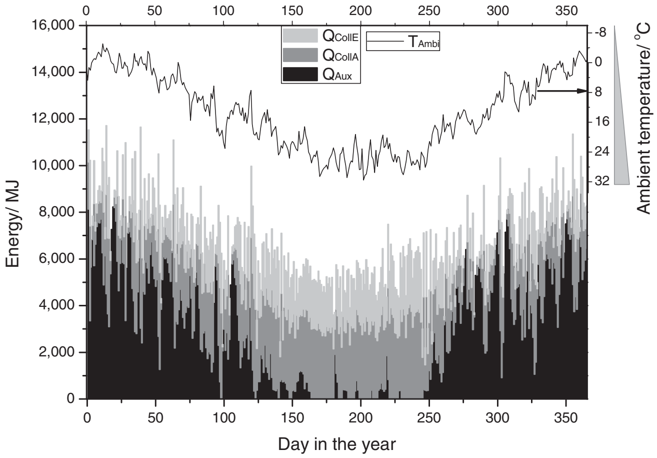


Figure 7 Daily solar radiation absorbed by collectors in section A (Q_{collA}), in section E (Q_{collE}), and the daily auxiliary heat (Q_{aux}) of the SWHS and the ambient temperature in a year.

1. The curve of the ambient temperature fluctuates day by day, but has a general tendency of rising from January to July and then decreasing from July to December. The highest ambient temperature is 31.5°C on July 21.
2. The total solar radiation absorbed in section A is larger than that in section E. In addition, the total absorbed solar radiation in summer is larger than that in winter. Higher auxiliary heat is required in winter, whereas auxiliary heat is seldom required in summer. The auxiliary heater is also more frequently used in winter.
3. The total energy required from the SWHS, Q_{load}, is the sum of absorbed solar radiation in sections A and E and the auxiliary heat. The required total energy is larger in the winter half of the year, owing to the lower ambient temperature. In addition, the required total energy has a contrary tendency against the ambient temperature.

The daily integrated and annually average solar fractions of the SWHS are displayed in Figure 8. The highest and the lowest daily solar fractions are 1.0 and 0.026, respectively, and the annually average solar fraction is 0.56. In winter, the daily solar fraction points are dispersive and fluctuating, whereas in summer the daily solar fraction points are concentrated and steady. From May 10 (day 164) to August 11 (day 254), there are many days whose daily solar fraction is 1.0, which means the solar collectors could supply the whole required energy for water heating. This phenomenon agrees well with the auxiliary heat curve in Figure 7. The integrated solar fraction denotes the integrated solar fraction from January 1 to the *n*th day, which could be expressed as

$$f_n = \frac{\sum_{i=1}^{n} (P_{load,i} - P_{aux,i})}{\sum_{i=1}^{n} (P_{load,i})} \tag{19}$$

Figure 7 shows that the integrated solar fraction first unstably increases from day 1 to day 96, then steadily rises from day 96

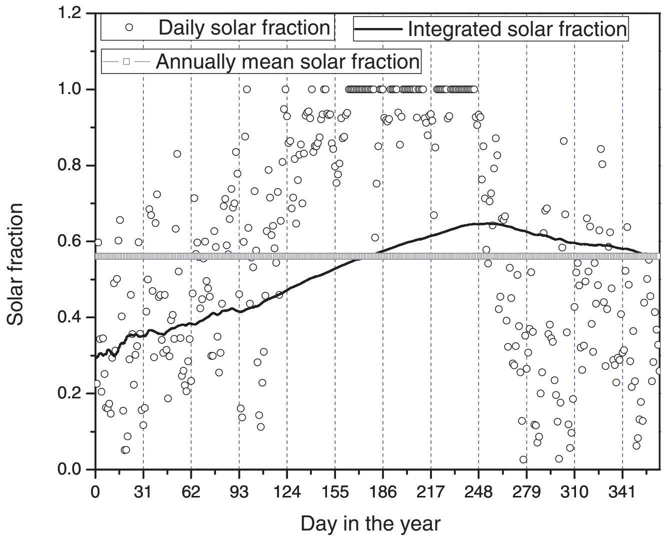


Figure 8 Daily solar fraction, integrated solar fraction, and annually average solar fraction of the SWHS throughout the year. (Color figure available online.)

to day 250 and finally gradually declines from day 250 to the end of the year. The highest integrated solar fraction is 0.647 in September 10.

SWHSs With Different Collector Areas

During the SWHS construction process, the practical collector area available might be limited to or larger than the theoretically designed collector area. In Figure 9, we present the annual total required energy and average solar fraction against the solar collector areas. The theoretically designed solar collector area is the baseline, and the proportion of the practical collector area to the designed area (PTDA) is set as the horizontal axis. From the figure, it is found that:

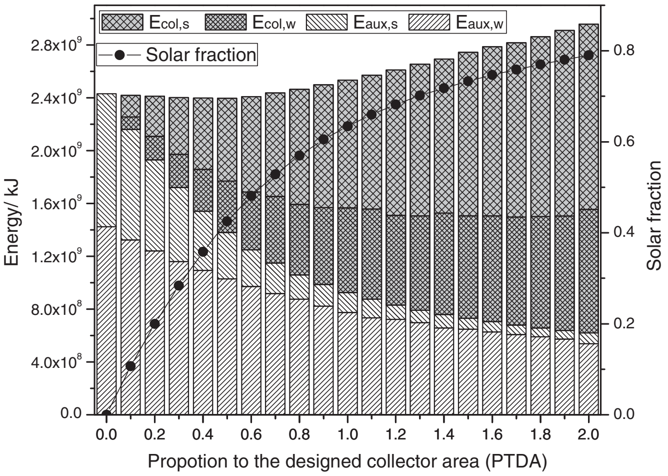


Figure 9 Energy absorbed by the solar collectors in summer ($E_{col,s}$) and in winter ($E_{col,w}$), energy supplied by auxiliary heater in summer ($E_{aux,s}$) and in winter ($E_{aux,w}$), and the solar fractions against the collector area proportion to the designed area (PTDA, $PTDA = \frac{A_{col,practical}}{A_{col,designed}}$).

1. When no solar collector is installed, the system energy load is 1.43×10^9 kJ. Also, with PTDA smaller than 0.6, the required total energy remains the level. The total required energy rises gradually with PTDA increasing from 0.6 to 2.0 due to the higher energy loss in collectors and pipes.
2. When PTDA increases, the auxiliary heat both in summer and in winter decreases, whereas the collector absorbed heat in both summer and winter increases. Moreover, the auxiliary heat in summer decreases sharply with PTDA rising from 0 to 0.8, and after that, its declination is small. The auxiliary heat in winter also declines gradually with PTDA rising. The auxiliary heat in winter is larger than that in summer, and its difference is extended with PTDA rising. On the other hand, the collector absorbed energy in summer and winter both increase with PTDA rising. In addition, the required total energy in summer is smaller than that in winter.
3. The solar fraction also rises with PTDA increasing. But the rising tendency is more significant when PTDA is smaller than 0.8. In addition, the solar fraction is larger than 0.5 with PTDA larger than 0.7.

From the preceding analysis, we could conclude that increasing the solar collector area is benefit to the system's thermal performance. However, the practical collector area depends on the construction site conditions. Moreover, enlarging the collector area would raise the investment.

ECONOMIC EVALUATION

The n year total investment $C_{0,N}$ of the original GGS is

$$C_{0,N} = \sum_{i=1}^{n} P_{0,gas} = \sum_{i=1}^{n} \left[\frac{Q_{load}}{q_{gas}} c_{gas}(1 + f_r)^n \right] \tag{20}$$

and the n year total investment for the SWHS C_N is

$$C_N = \sum_{i=1}^{n} (P_{gas} + C_{om,n} - C_{CO2}) + P_{inv} - P_{inv,res} \tag{21}$$

where $c_{gas} = 2.3$ yuan/m^3 and $f_r = 4.9\%$. The lifetime of the designed SWHS is 20 years.

The construction cost and transportation costs are assumed to be 15% of the equipment investment. Thus, the total equipment investment of the SWHS is

$$P_{inv} = 1.15 \times (P_{col} + P_{pum} + P_{tak} + P_{pip}) \tag{22}$$

The first-year operation and maintenance cost of the SWHS $C_{om,1}$ is the expense of management, control, and solar collector maintenance. The annual operation and maintenance cost after the first year of operation increases year by year, and can be expressed by the following equation:

$$C_{om,n} = C_{om,1}(1 + \varepsilon_{om})^{(n-1)} \tag{23}$$

where $\varepsilon_{om} = 4.9\%$.

Table 2 Initial system investment of the SWHS

Subjects [unit]	Value
Solar collectors [yuan/m^2]	1500
Water tanks [yuan]	60,000
Control system [yuan]	50,000
Water pumps [yuan]	42,120
Valves and pipes [yuan]	30,000
First year operation and maintenance cost [yuan]	30,000

The equipments in the system are assumed to devalue according to the inflation rate, which could be expressed as

$$P_{inv,res} = P_{inv}(1 + f_r)^{-n} \tag{24}$$

Carbon dioxide (CO_2) equivalent released from the natural gas is calculated to be 125.30 tonnes CO_2 emissions TJ^{-1} of energy from the natural gas. According to the carbon credit price of 10.12 Euros tonne^{-1} CO_2 [24] and the conversion rate for yuan to Euro at 8.60:1 [25] as reported on November 11, 2011, the cash inflow generated by carbon credits in the first year of operation is estimated by

$$C_{CO2} = (Q_{load} - Q_{aux}) \times 125.30 \times 10.12 \times 8.60 \tag{25}$$

The cash inflow generated by carbon credits after the construction of SWHS will gradually increase with inflation.

Table 2 shows the initial system investment of the SWHS, and Table 3 presents the total investment of the original GGS and the SWHS during the lifetime with PTDA between 0.1 and 2.0. It is found from Table 3 that the first-year investment of the SWHS is around 1.53 million yuan, and its payback period is 7.4 years. The first-year investment increases with the collector area enlarging. The payback period of the SWHS is smaller than its designed lifetime when PTDA is larger than 0.2. As PTDA is augmented, two things occur that work in opposite directions with respect to the system payback period. A higher PTDA results in a lower auxiliary heat and hence yields a smaller annual gas cost and annual investment. On the other hand, enlarging the PTDA would increase the initial investment, and so increase the total investment. With the influence of the initial investment stronger than the fuel saving, the payback period increases when PTDA is larger than 0.4. However, because the auxiliary fuel saving is too small, the system is not cost-effective when PTDA is 0.1. The system has the shortest payback period when PTDA is 0.4. When PTDA is 1.0, the system has the smallest total investment during its lifetime. Besides, when PTDA is larger than 0.2, 20 years of total investment for the SWHS is smaller than the original GGS investment. According to Figure 9, the solar fraction is larger than 0.5 when PTDA is larger than 0.7. Therefore, taking the system's thermal and economic performances into consideration, the PTDA range of 0.7–1.0 is finally suggested for the practical SWHS.

Evacuated tube solar collectors have been developed in China for nearly 30 years. There are several famous companies in China whose evacuated tube solar collectors are cheap, stable, and well accepted. Northwest China has abundant solar radiation

Table 3 Total investment of the original GGS and the SWHS in 20 years

		SWHS [yuan] PTDA										
Year	GGS [yuan]	0.1	0.2	0.4	0.6	0.8	1.0	1.2	1.4	1.6	1.8	2.0
0[a]	0	344173	476225	740330	1004440	1268540	1532650	1796750	2060860	2324960	2587070	2853170
1	171704	229093	247999	289234	336550	389414	445429	503697	563375	623956	684964	746565
2	351822	404785	415711	444579	485906	538601	597752	661519	728176	796682	866063	936660
3	540765	589506	591525	606346	640318	691762	753130	821593	894498	970244	1047336	1126296
4	738967	783929	776092	775156	800389	849499	912169	984535	1062970	1145289	1229448	1316157
5	946881	988773	970111	951669	966760	1012446	1075508	1150993	1234255	1322492	1413088	1506953
6	1164982	1204810	1174327	1136593	1140115	1181280	1243822	1321649	1409045	1502563	1598981	1699422
7	1393770	1432867	1409541	1330683	1321183	1356719	1417830	1497228	1588074	1686244	1787885	1894337
8	1633769	1673831	1646610	1534748	1510745	1539530	1598296	1678497	1772117	1874323	1980597	2092511
9	1885528	1928657	1896458	1749660	1709636	1730536	1786035	1866274	1961999	2067632	2177962	2294800
10	2149623	2198372	2150077	1976353	1918755	1930615	1981921	2061431	2158597	2267059	2380874	2502110
11	2426659	2484080	2438534	2215833	2139070	2140715	2186890	2264904	2362849	2473546	2590286	2715403
12	2717269	2786972	2732981	2469186	2371619	2361852	2401947	2477694	2575759	2688102	2807213	2935705
13	3022119	3108332	3044660	2737581	2617528	2595123	2628176	2700879	2798405	2911811	3032743	3164109
14	3341908	3449545	3364911	3022284	2878007	2841713	2866743	2935620	3031946	3145832	3268042	3401789
15	3677365	3812108	3695181	3324660	3154369	3102899	3118910	3183169	3277632	3391418	3514363	3650003
16	4029260	4197636	4037037	3646189	3448033	3380068	3386041	3444880	3536812	3649917	3773057	3910108
17	4398398	4607879	4402173	3988473	3760537	3674720	3669614	3722217	3810945	3922787	4045583	4183563
18	4785624	5044728	4792423	4353247	4093548	3988480	3971230	4016768	4101612	4211605	4333515	4471947
19	5191824	5510231	5189775	4742395	4448879	4323117	4292627	4330256	4410527	4518080	4638563	4776970
20	5617927	6006608	5606383	5157962	4828495	4680550	4635696	4664552	4739549	4844068	4962578	5100482
Payback period [years]	—	>20	18.5	5.1	5.4	6.3	7.4	8.7	10.1	11.6	13.1	14.7

[a] Note that the year 0 refers to the initial system investment.

but is still economically underdeveloped. Moreover, the water heating system is one of the necessities in people's daily life. Thus, designing a SWHS for substituting the original fuel boiler water heating system is of high importance to the economical development and environmental conservation in this region.

CONCLUSIONS

In this study, an SWHS is designed to substitute for the existing GGS of a four-star hotel in Xi'an. The system transient performance measures, such as the water temperatures at the collector outlet and in the supply tank, the auxiliary heat, and the solar fraction, are analyzed using TRNSYS program. The techno-economics of the SWHS are also evaluated for practical conditions with the solar collector area varying from zero to twice the designed value. The main conclusions can be summarized as:

1. The water temperatures at the solar collector outlet and in the tanks are much higher in summer than in winter. The solar radiation and ambient temperature have positive effect on the water temperature. The auxiliary heat is much more frequently and abundantly required in winter than in summer. And the annual average solar fraction of the designed SWHS is 0.56.
2. The economic analysis results validate the feasibility of the SWHS. The first-year total investment is near 1.53 million yuan and the payback period is 7.4 years.
3. For practical conditions, changing the collector area could significantly influence the system's thermal performance and techno-economics. A solar collector area proportion to the designed collector area of 0.7–1.0 is suggested for practical construction.

NOMENCLATURE

a	collector efficiency coefficient (—)
A_{col}	solar collector area (m^2)
A_{cor}	corrected solar collector area (m^2)
b	collector efficiency coefficient (—)
B_1	flow rate of solar collectors (L/(m^2-s))
B_2	daily average hot water productivity (m^3/m^2)
c	collector efficiency coefficient (—)
C_{CO2}	cash inflow generated by carbon credits (yuan)
c_{gas}	gas price (yuan/m^3)
C_h	Hazen–Williams coefficient (—)
$C_{om,n}$	nth year operation and maintenance cost (yuan)
c_p	water specific heat (kJ/(kg-K))
f	solar fraction (—)
f_r	inflation rate (—)
g	acceleration of gravity (m/s^2)
$\bar{H}_d$	annually average diffuse solar radiation on the horizontal surface (W/m^2)
$\bar{H}_{hor}$	annually average total solar radiation on the horizontal surface (W/m^2)
k_h	hourly variation coefficient (—)
L_{th}	pipeline length (m)
M	daily hot water consumption (kg)
$P_{0,col}$	pressure drop in solar collectors (kPa/m^2)
$P_{0,gas}$	annual natural gas cost in the original GGS (yuan)
P_{col}	investment of the solar collectors (yuan)
P_{gas}	annual natural gas cost in the designed SWHS (yuan)
P_{inv}	initial equipment investment (yuan)
$P_{inv,res}$	salvage value at the end of the nth year (yuan)
P_{loss}	heat loss through the pipes (W)
P_{pip}	investment of the pipelines (yuan)
P_{pum}	investment the pumps (yuan)
P_{tak}	investment of the tanks (yuan)
q_{gas}	gas calorific value (kJ/m^3)
q_j	circulation or auxiliary heater flow rate (kg/s)
R_b	ratio of beam radiation to that on the horizontal surface (—)
R_{cor}	collector compensation area ratio (—)
ref	ground reflectance (—)
T^*	normalized temperature difference (m^2-°C /W)
T_c	cold water temperature (°C)
T_{end}	temperature in the hot water tank (°C)
Time	annually average daily solar duration (hour)
T_w	water temperature (°C)
v	water speed in the pipelines (m/s)

Greek Symbols

β	collector slope angle (°)
η_L	loss coefficient of water pipe and tank (—)
τ	time (s)
ε_{om}	annual increasing rate of operation and maintenance costs (—)
ρ	water density (kg/m^3)
ΔT_{CS}	water temperature difference between circulation and supply tanks (°C)

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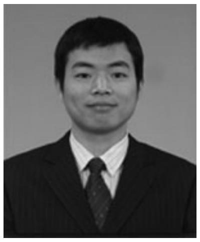

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