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Solar Water Heating Systems Applied to High-Rise Buildings—Lessons from Experiences in China

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Abstract: High-rise buildings have a significant impact on the surrounding environment. Building-integrated solar water heating (SWH) systems are effective ways to use renewable energy in buildings. Impediments, such as security concerns, aesthetics and functionality, make it difficult to apply SWH systems in high-rise buildings. At present, only China uses SWH systems on a large scale in such buildings. What are China's experiences and lessons learned in applying SWH systems in high-rises? Are these experiences scalable to other countries? This study used a combination of field investigation, literature review and case study to summarize 36 systems that had been in operation for 1–14 years. System types, collector types, installation methods, types of auxiliary heat sources, economic performance and various basic principles were summarized. The economic performance of SWH systems in high-rise buildings was analyzed and verified by a case study in Shanghai. The results show that the installation of SWH systems in high-rise buildings is feasible and reliable. Individual household systems (61%) were more popular than centralized systems (25%) and hybrid systems account (14%). The average area of solar collectors per household was 2.17 m^2/household, the average design solar fraction was 52%. Flat plate solar collectors (53%) was the most commonly used collector, while electric heating elements (89%) were the most common auxiliary heat sources for SWH systems, followed by gas water heaters and air source heat pumps. The cost of SWH systems per m^2 of a building area was between 22 CNY/m^2 to 75 CNY/m^2. China's unique practical experience gives a reference for other countries in their efforts to make high-rise buildings more sustainable.

Keywords: Solar water heating system; high-rise building; building-integrated solar thermal; solar fraction; levelized cost of heat

1. Introduction

Solar thermal heating systems are utilized in millions of residences worldwide [1] and have made a great contribution to the sustainable development of the earth [2]. Solar water heaters are not only widely used in rural China [3] but also in rural areas in Australia [4], Turkey [5], India [6], and parts of Africa [7]. However, it is more urgent for urban buildings to improve energy efficiency and reduce emissions [8]. Building-integrated solar thermal systems are effective ways to use renewable energy in buildings [9]. Since urban buildings are located in areas with high population and development density, the occlusion between buildings is severe. The space required for the installation of solar collectors is often lacking [10].

Despite the challenges, experts from countries and regions such as China [11–13], Germany [9], Greece [14], Netherlands [15], Israel [16], Argentina [17], Korea [18], Hong Kong [19–21], Iran [22,23], Brazil [16,24], Turkey [25] and Vietnam [26], are still actively exploring the potential for and possible technical solutions to apply solar water heating (SWH) systems in urban buildings. In China, the application of solar hot water in urban buildings has received considerable support from the government [27]. Since 2007, in order to increase energy efficiency in buildings and promote the application of renewable energy therein, under the guidance of national and local building energy conservation codes, 23 provinces and three municipalities issued mandatory installation policies for SWH systems in buildings with less than 12 floors (some provinces and municipalities required six floors). The implementation of this policy resulted in dramatic changes, with the market share of SWH in the urban domestic hot water market reaching 24% [28] over the past ten years.

Increases in urbanization and technological advancement have led to buildings of ever-increasing height. High-rise buildings have a significant impact on the surrounding environment [29], and their shadows significantly reduce the possibility of applying solar energy for surrounding low-rise buildings. However, high-rise buildings can accrue substantial benefits from exposure to more solar radiation. Does this mean that SWH systems are feasible in high-rise buildings? Is this especially true in terms of technical and economic performance?

Over the past few years, there has been a plethora of research and reviews on low-rise buildings and building-integrated solar thermal (BIST) systems for small buildings, especially low rises [9,30–36]. For buildings with a height of 35–100 meters or 12–33 floors, previous studies focused on policy recommendations [37–39], or case studies [40,41], but there has been no comprehensive systematic summary of the safety, economic performance, aesthetics and technical solutions of SWH systems.

By utilizing an investigation of existing high-rise buildings using SWH systems in China, the experience and lessons learned from SWH system application in high-rise buildings will be summarized in this study. The technical solutions and economic performance of SWH systems will be systematically analyzed with a case study in Shanghai.

Solar hot water has great potential in urban buildings [42]. The technical recommendations based on the research presented in this paper will not only help improve the energy efficiency of high-rise buildings and reduce the energy cost for urban residents but also help governments around the world to achieve renewable energy application goals, promote technological innovations, increase employment and improve people's livelihoods in developing countries.

2. Methodology

A literature review, deep interviews, a questionnaire survey and field investigation were carried out in this study. From 2016 to 2018, government officials, real estate developers, designers, solar water heater manufacturers, property management personnel and users were interviewed. A total of 36 SWH systems in high-rise buildings were investigated on-site; 200 questionnaires were distributed to the stakeholders and the valid and effective samples numbered 156. There were 26 questions in the questionnaire that covered the whole process of design, construction, commissioning, operation and maintenance of solar hot water systems in high-rise buildings, including solar fraction determination, hot water usage, system types, collector types, installation method and common malfunction.

The systems were randomly selected from 21 cities nationwide, from Beijing in the north to Shenzhen in the south, as shown in Figure 1. The 36 SWH systems in high-rises were built from 2005 to 2018 with a height from 35 to 100 meters. The average height of the buildings is 62 meters with 21 floors; Figure 2 shows the distribution of the height of the buildings by years; the dotted line in Figure 2 shows that there is a trend toward taller buildings over the past 14 years.

Figure 1. Geographical distribution of surveyed projects.

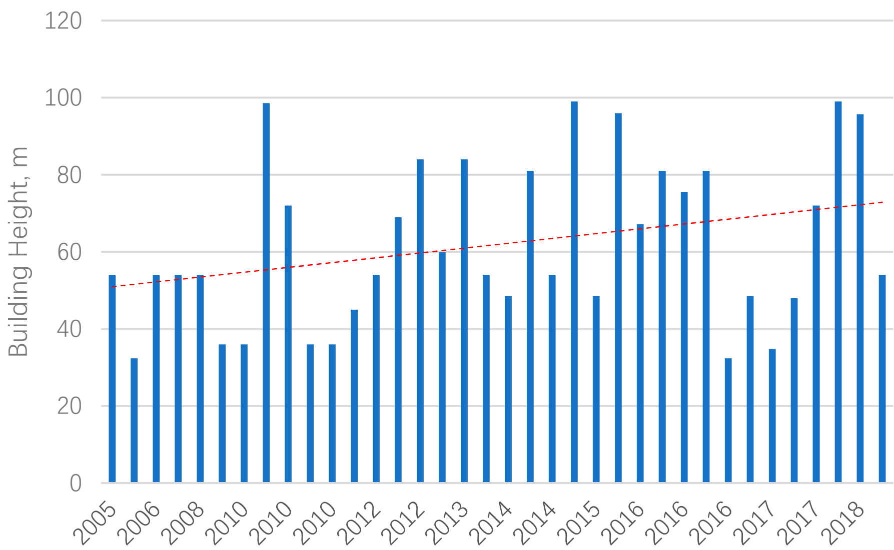


Figure 2. The height of the investigated high-rise buildings by year completed.

Theoretical calculations and field measurements of a household SWH system in a high-rise residential building in Shanghai were conducted. The index of levelized cost of heat (LCoH) recommended by International Energy Agency (IEA) Task 54 [43] was used to evaluate its economic performance.

The measurement method is based on the Evaluation Standard for Application of Renewable Energy in Buildings (Chinese standard GB/T 50801-2013) [44]. The measured parameters include ambient temperature, wind speed, aperture area of a solar collector, solar radiation on the plane of the solar collector, water volume in the water tank and water temperature in the water tank. Equations (1)–(4) are used to calculate the solar fraction of a solar water heating system.

$$Q_z = \sum_{i=1}^{n} m_{zi}\rho_w C_w (t_{dzi} - t_{bzi})\Delta T_{zi} \times 10^{-6} \quad (1)$$

Q_z is the total energy consumption of the solar water heating system in MJ; n is the total number of records; m_{zi} is the hot water flow rate recorded in i-th test in m^3/s; ρ_w is the density of hot water in kg/m^3; c_w is the specific heat capacity of water in J / (kg·K); t_{dzi} is the hot water temperature recorded in i-th test in °C; t_{bzi} is the cold water temperature recorded in i-th test in °C; ΔT_{zi} is the time step in s, in this case, $\Delta T_{zi} = 10$ s.

$$Q_s = \sum_{i=1}^{n} m_{si}\rho_{sw}C_{sw}(t_{dsi} - t_{bsi})\Delta T_{si} \times 10^{-6} \quad (2)$$

Q_s is the total heat gain of solar collectors in MJ; m_{si} is the working fluid flow rate in the heat collection system recorded in i-th test in m^3/s; ρ_{sw} is the density of collector fluid in kg/m^3; c_{sw} is the specific heat capacity of a collector fluid in J/(kg·K); t_{dsi} is the collector fluid temperature at the outlet recorded in i-th test in °C; t_{bsi} is the collector fluid temperature at the inlet recorded in i-th test in °C; ΔT_{si} is the time step in s, in this case, $\Delta T_{si} = 10$ s.

$$f_j = \frac{Q_s}{Q_z} \quad (3)$$

f_j is the solar fraction obtained in short-term tests under specific solar radiation conditions in %.

$$f = \frac{x_1 f_1 + x_2 f_2 + x_3 f_3 + x_4 f_4}{x_1 + x_2 + x_3 + x_4} \quad (4)$$

f is the calculated annual solar fraction of the system in %; x_1 is the number of days when local solar radiation is less than 8 MJ/m^2; x_2 is the number of days when local solar radiation is equal to or higher than 8 MJ/m^2, but less than 13 MJ/m^2; x_3 is the number of days when local solar radiation is equal to or higher than 13 MJ/m^2, but less than 18 MJ/m^2; x_4 is the number of days when local solar radiation is higher than 18 MJ/m^2; f_1 is the SF when local solar radiation is less than 8 MJ/m^2 in %; f_2 is the SF when local solar radiation is equal to or higher than 13 MJ/m^2, but less than 18 MJ/m^2 in %; f_3 is the SF when local solar radiation is equal to or higher than 13 MJ/m^2, but less than 18 MJ/m^2 in %; f_4 is the SF when local solar radiation is higher than 18 MJ/m^2 in %. The measurement variables, equipment and accuracy are listed in Table 1:

Table 1. The measurement variables, equipment and accuracy for the case study.

Measured Variables	Equipment	Accuracy
Ambient air temperature	Thermometer	±0.1 K
Wind speed	Anemometer	±0.1m/s
Solar radiation	Pyranometer	±10%
Water temperature	4-wire PT100	±0.5K
Collector fluid temperature	4-wire PT100	±0.5K
The total water flow rate in the water heating system	Flowmeter	±1%
The collector fluid flow rate in the solar collector	Flowmeter	±1%

3. Results

3.1. Three Basic Principles

It is a challenge for both architects and manufacturers to apply SWH systems in high-rise buildings so that they provide highly efficient domestic hot water solutions, and simultaneously ensure the safety and reliability of the systems. Three principles are suggested as prerequisites of BIST installations, namely, aesthetics, solar thermal performance and solar-control requirements [9], as well as three basic building requirements, namely, that they are functional, constructive and formal [44]. However, for SWH systems in high-rises, safety is the most important, followed by aesthetics and functionality.

(1). Safety

Over the past 14 years, none of the investigated 36 systems experienced collectors falling from their edifices, showing that applying SWH systems in high-rises is safe. Table 2 shows the types of SWH systems commonly used in high-rise buildings. The safety hazards of these systems are mainly manifested in water leakage, short-circuiting, collapse and lightning strikes during use. Such accidents involving safety in SWH systems mostly occur in areas of severe cold. The most common of these is water leakage caused by vacuum tube explosion, fire in the insulation layer caused by inferior quality electric heating rods, and formation of ice on roofs caused by water leakage.

The weight of solar collectors adds an additional load to the building structure, however. The average weight of a compound parabolic collector with a U-shaped copper pipe inside (CPC) or a flat plate collector (FPC) is approximately 20 kg/m^2 while operating with water or other working fluid inside, but an all-glass evacuated tubular collector (AGETC) weighs about 50 kg/m^2. Table 3 lists the weight of different types of solar collectors commonly used in high-rise residential buildings. The safety issue must be addressed by improving the load capacity of building components, and reserving appropriate installation space and maintenance space for solar collectors on the external walls of buildings. In order to prevent strong winds from separating solar collectors from their fixtures, wind load must also be considered in the design of connecting fasteners, including the depth and strength of these fasteners, taking into consideration the most adverse climatic conditions. In terms of safety, the collector type of choice is FPCs and they are the most commonly used collectors in high-rise residential buildings.

(2). Aesthetics

In addition to being safe, solar collectors must satisfy requirements for architectural aesthetics. These requirements are summarized by IEA Task 41 Solar Energy and Architecture for aesthetic quality of buildings integrated solar collectors [45], including natural integration, architecturally pleasing design, aesthetic composition of colors and materials, size that suits the harmony and combination of the structure, consistency with the context of the building, and well composed and innovative design.

In order to receive sunlight, solar collectors must be placed outdoors. For the individual household SWH systems commonly used in high-rise buildings, collectors are usually installed only on the exterior walls or balcony railings. The installation of collectors will destroy the original design style of the building facade. That is why SWH systems are often considered to be troublesome by architects. The successful implementation of SWH systems in high-rise buildings requires designer involvement in the integrated design process from the planning and design stage of the project [46–48]. Carefully integrated design of solar thermal components and building envelopes enables limited improvement in the overall energy performance of the buildings, including an increase in energy generation potential from SWH systems and the reduction of cooling loads. To achieve these objectives, architects should fully understand the material characteristics and the safety requirements of the collector products, and integrate collectors as one of the performance elements of the architectural style in the facade design of the building.

(3). Functionality

A total of 86% of the investigated residents expressed satisfaction with the results of SWH systems. Only a few households located on the ground floor or severely obstructed by adjacent buildings reflected that the SWH system could not produce enough hot water and the electricity consumption was too large. The problems reported by the survey users include: insufficient hot water in winter (29%), water leakage (21%), unstable water temperature (10%), excessive power consumption of circulating water pumps (7%), and overheating in summer (5%).

Table 2. Types of solar water heating (SWH) systems commonly used in high-rise buildings.

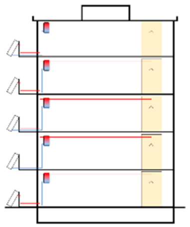
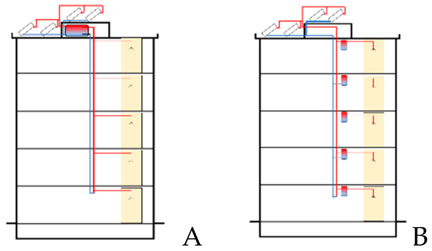
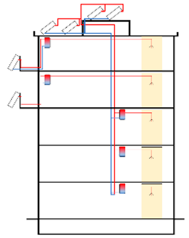
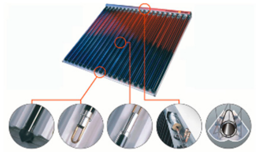
System Type	**Individual Household System**	**Central System**	**Hybrid System**
System schematic			
System description	The collectors are installed on the balcony, or walls individually. The heat obtained by the solar collector is stored in individual water tanks by heat exchangers inside in households.	Solar collectors are centrally installed on the roof, the heat obtained by the solar collector is stored in a central water tank which supplies hot water to households (A). Alternatively, absent a central water tank, heat obtained by the solar collector is stored in individual water tanks by heat exchangers inside in households (B).	Some collectors are installed centrally on the roof and partially on balconies or walls between windows. This is a hybrid of an individual household system and a central system.
Collector area	1.5–3.0 m^2/household	0.67–3.9 m^2/household	1.4–2.8 m^2/household
Advantages	Property rights are clear, the system is simple, the performance is stable, and the control is flexible.	The collectors are installed on the roof, which does not affect the appearance of the building. The system has a high collection efficiency.	Maximizes solar energy collection.

Table 2. *Cont.*

System Type	Individual Household System	Central System	Hybrid System
Disadvantages	The collectors of the households in bottom floors are easily shaded by other buildings, which reduces the thermal performance. The use point is far from the balcony, a high heat loss from long pipelines will increase the energy consumption of the auxiliary heat source [51]. It has a significant influence on the appearance of the building, and the heat collection is greatly affected by the duration of exposure to sunshine. The sunshine exposure of households below the 4th floor is affected by shading, which decreases system efficiency.	The property rights are not clear, while the use factor is low and the actual efficiency is low. Users need to share the costs for assisted heating and water charges, so the system needs to be measured and charged to households. A building with fewer active households will pay a higher price. The system requires an increased power capacity due to the use of electric-assisted heating with extreme heating power, which will increase the initial investment. The heat loss of the pipeline will increase the cost of hot water due to the protracted operation of the auxiliary heating system. The installation area of the collectors is limited by the roof area and is often less than the demand, which results in a low solar fraction [40].	Long pipes, considerable heat loss. For households under 10th floor, cold water in the pipe needs to be drained before using hot water.
Cases			

Table 3. A technical and economic comparison of solar collectors commonly used in high-rise buildings.

	FPC	HPETC	CPC	UPETC	AGETC
Pictures of collectors					
Coefficient of performance	$\kappa\theta = 1, \eta_0 = 0.799$ $a_1 = 2.41, a_2 = 0.015$	$\kappa\theta = 1, \eta_0 = 0.618$ $a_1 = 1.38, a_2 = 0.018$	$\kappa\theta = 1, \eta_0 = 0.632$ $a_1 = 0.338, a_2 = 0.011$	$\kappa\theta = 1, \eta_0 = 0.632$ $a_1 = 0.638, a_2 = 0.016$	$\kappa\theta = 1, \eta_0 = 0.636$ $a_1 = 0.654, a_2 = 0.013$
Aperture area	2.88 m^2	2.1 m^2	2.1 m^2	2.1 m^2	2.1 m^2
Temperature	60–80 °C	60–120 °C	60–120 °C	60–120 °C	60–100 °C
Weight*	17.5 kg/m^2	23.1 kg/m^2	18.5 kg/m^2	22.0 kg/m^2	50 kg/m^2
Incremental cost**	40 CNY/m^2	55 CNY/m^2	65 CNY/m^2	57 CNY/m^2	32 CNY/m^2
Durability	Strong weather durability with a thicker tempered glass cover.	More susceptible to breaking with thinner glass.	The sealed silicone ring is easy to age, causing the entire tube to lose vacuum.	Same as HPETC and CPC	Fragile and prone to more maintenance.
Installation	More walls, fewer roofs	More roofs, fewer walls	Walls and roofs	Walls and roofs	More roofs, fewer walls
Advantages	Easy to install, safer	Higher efficiency	Higher efficiency	Higher efficiency	Cheap
Disadvantages	Weak wind resistance	Difficulty for integration	Difficulty for integration	Difficulty for integration	Fragile

* The total weight of the collector in operation with a heat transfer medium; ** The incremental cost refers to the increase in building construction cost due to the installation of SWH systems. $Incremental\ Cost = \frac{The\ cost\ of\ solar\ water\ heating\ system\ equipment+installation\ fees}{The\ building\ area\ served\ by\ the\ solar\ water\ heating\ system}$, CNY/m^2

To ensure that SWH systems produce enough hot water, the solar collector surface should receive at least four hours of sunshine during the winter solstice [49]. For high-rise buildings, the ideal installation location to meet the sunshine requirement is on the rooftop of the building. However, because of high building density, roof areas often fail to meet the solar collector requirement for the hot water demand of all households. Therefore, it is not enough for high-rise buildings to provide domestic hot water to all users by installing solar collectors on roofs. Additional installation space is needed to improve the solar fraction of SWH system, e.g., on exterior walls, balconies and bay windows. The solar fraction (SF) is the fraction of the heating demand covered by solar energy. A higher solar fraction means a higher contribution of solar energy in a SWH system.

Although solar collectors can also be used as a sunshade component [50], if solar collectors are installed on a balcony or wall of a high-rise building, mutual shading between buildings, as well as shade covering collectors of residents on lower floors [50], will reduce the efficiency of the system and increase the energy consumption of auxiliary heat sources. Usually, the aperture area of the collector is half-blocked, and the energy consumption of the auxiliary heat source is correspondingly doubled [51].

3.2. Hot Water Usage and Storage Tank Capacity

Bathing with hot water has become a basic need for urbanites in China. Daily hot water consumption for this demographic is mainly used for bathing and cooking, among which bathing is the primary use; the peak of hot water consumption is from 19:00 to 23:00 in the evening and the water supply temperature is set between 42 °C and 53 °C [52]. Corresponding hot water consumption is between 31 and 47 L per person per day for different seasons and climates [53]. According to the Code for Design of Building Water Supply and Drainage (GB50015–2009) [54] and practical experience, the daily hot water usage of each household is assumed to be 100–150 L, which is determined by the size of the flat and the size of the family.

3.3. System Types

Although thermosiphon solar water heaters dominate the solar thermal market in China's rural areas, split pressure systems are the most commonly used solar water heating system for high-rise buildings. The types of SWH systems commonly used in high-rise buildings mainly include centralized systems, household systems and hybrid systems. High-rise buildings have a large number of users, high demand for hot water and a limited roof area. A centralized hot water system with collectors installed on a roof has a low solar fraction for each household. The massive heat loss caused by the long pipeline greatly reduces the economics of an SWH system. Qu Yan [55] has carried out calculations and statistics on the available area of the rooftops for SWH systems and the number of floors in dozens of high-rise residential buildings in Shanghai with different configurations (one ladder with two households, one ladder with three households and one ladder with four households). The results show that the available roof area of the layout for one ladder with two households can only install solar collectors to meet the hot water demand for users in 10–14 floors. The available roof area of the layout for one ladder with three households and four households can only install solar collectors to meet the hot water demand for users in 7 floors.

For household systems, the low-rise residents are affected by the occlusion of other buildings, and the actual heat gain of solar collectors is also low. Therefore, the system with the higher solar fraction is a hybrid combining centralized and household systems: household systems for high-rise households and centralized systems for low-rise households. However, the cost of a hybrid system is considerable.

Table 2 lists the common types of SWH systems used in high-rise residential buildings. In the 36 SWH systems, individual household systems account for 61%, centralized systems account for 25%, and hybrid systems account for 14%.

The collector area per household is determined by the hot water demand and influenced by the installation location. The collector area per household for the household system is between 1.5 m^2 and 3.0 m^2. The collector area per household in centralized systems is closely related to the installation location and varies greatly. If the installation location is limited to the roof, the installation area is insufficient, and the minimum is only 0.67 m^2 per household. If a roof is designed for the installation of the collectors as a floating board, the installation area can be expanded considerably. The collector area per household in high-rise buildings can exceed the household system, up to 3.9 m^2. For hybrid systems, the collector area per household is between 1.4 m^2 and 2.8 m^2. In the 36 systems, the average area of solar collectors per household is 2.17 m^2/household, the average design SF is 52%.

3.4. Collector Types

There are five types of solar collectors in use, of which, FPCs account for 53% (19 systems), CPCs account for 14% (5 systems), evacuated tubular collectors with a U-shaped copper pipe inside (UPETC) account for 11% (4 systems), evacuated tubular collectors with a heat pipe inside (HPETC) account for 6% (2 systems), all-glass evacuated tubular solar collectors (AGETC) account for 17% (6 systems).

Heat collection efficiency is an essential performance indicator for solar collectors. The efficiency varies greatly for different incidence angles and different climates [56]. To compare the efficiency of different types of solar collectors used in high-rise buildings, the efficiency equations for each type of solar collectors are listed in Table 3. Efficiency equations were obtained from the Solar Keymark database for comparison with the same test standard (ISO 9806:2017) for different types of collectors. Equation (5) is the efficiency equation for solar collectors.

$$\eta = \kappa\theta \cdot \eta_0 - a_1 \frac{T_m - T_a}{G} - a_2 \frac{(T_m - T_a)^2}{G} \quad (5)$$

where:

η is the collector efficiency;
η_0 is the peak collector efficiency;
κθ is the incidence angle modifier;
θ is the incidence angle for radiation in °;
a_1 is the heat loss coefficient of a collector at ambient temperature in W/(m^2K);
a_2 is the temperature dependence of the heat loss coefficient of a collector in W/(m^2K^2);
T_m is the mean solar collector fluid temperature in °C;
T_a is the ambient temperature in °C; and
G is the solar irradiance on the collector in W/m^2.

For the collector efficiency, the heat production by the solar collector can be calculated with Equation (6).

$$Q = A \cdot G \cdot \eta \quad (6)$$

where:

Q is the power produced by the solar collector in W; and
A is the gross area of the solar collector in m^2.

In addition to the five collectors mentioned in this article, there are many types of solar collectors used in buildings, including photovoltaic thermal hybrid solar collectors (PV/T) collectors, unglazed FPCs and polymeric collectors [57–59]. For high-rise buildings, the choice of FPC is due to safety concerns. As shown in Table 3, the biggest advantage of FPCs over evacuated tubular collectors is ease of installation and higher safety. They are lighter, have no fragile glass, and the color of their surfaces can be modified. These features make it easier to integrate FPC with building façade design. Figure 3 shows some cases in which the vacuum tubes were broken during use. Visa et al. [59,60] proposed shaped flat plate collector (FPC) assemblies to create/adapt different building facade styles. However, such products can only be customized in small quantities and are not scalable, resulting in high cost and little practical value.

(**a**) Multiple broken vacuum tubes in an evacuated tubular collector with a U-shaped copper pipe inside (UPETC).

(**b**) One broken vacuum tube in a compound parabolic collector with a U-shaped copper pipe inside (CPC).

Figure 3. Broken vacuum tubes in evacuated tubular collectors.

3.5. System Components

Water tanks, pipelines and circulating water pumps are essential components of SWH systems. In this survey, many system components were also found to be used improperly.

(1) Water tank: Due to inappropriate construction and installation, many pressurized water tanks leak water during use, especially through the connection between the water tank and pipeline. Poor quality of the inner tank of the pressurized water tank and improper connection of the temperature probe to the inner tank can cause the inner tank to leak.

(2) Pipeline: 58% of the collectors are connected using polypropylene random copolymer (PPR) pipes. The greatest problems with PPR pipes are water leakage, poor insulation and rust, as shown in Figure 4.

(**a**) Water leakage at the valve

(**b**) Pipe insulation layer falling off

(**c**) The end nozzle is directly blocked, and scale is deposited.

Figure 4. Common problems with piping systems.

(3) Hot water circulation pump: Problems with rust, start and stop control failure, lack of a backup pump and no noise reduction mechanisms were observed, as shown in Figure 5. The noise problem caused by circulating water pumps is the most common complaint from residents on the top floor.

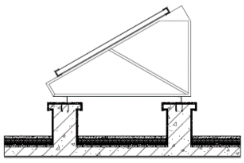
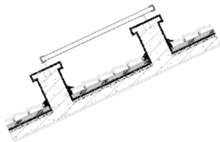
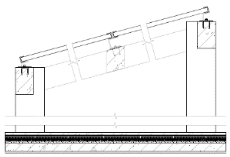
Figure 5. A circulating water pump without vibration reduction treatment.

3.6. *Installations*

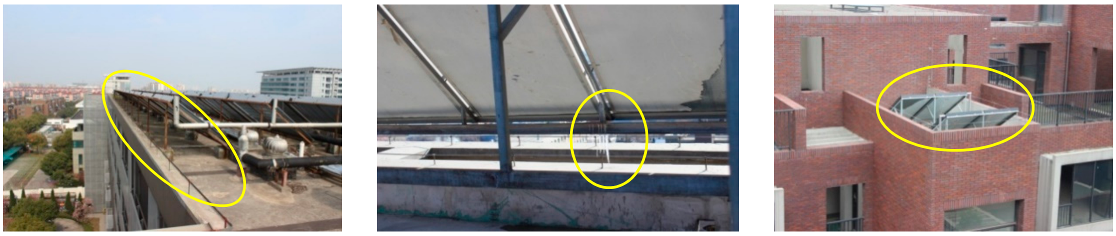
(1) Roofs

Rooftops are the best place for the installation of solar collectors, with sufficient exposure to sunshine and less impact on building facade design. Table 4 shows three integration form factors of the collector on three different roof structures. To ensure adequate installation area and sunshine for solar collectors, Type 3, a floating board, is used to support the solar collectors. The floating board not only prevents the roof from being exposed to direct sunlight in summer, therefore reducing the cooling load of the rooms on the top floor, but also forms a housing platform while meeting both technical and landscape requirements [61].

Table 4. Solar collectors installation modes on roofs.

Types	Type 1: Flat Roof	Type 2: Slope Roof	Type 3: Floating Board
Sketches			
Installation mode	Mounted on a bracket	Embedded roof	Mounted on a bracket
Angle	Local latitude	Same as the slope of the roof	Local latitude
Cases			

Because high-rise buildings mainly have flat roofs, none of the investigated projects used the roof-mounted installations that are more common in Europe. Limited by installation area, the roof installation collector needs to avoid installation in a position of minimal efficacy and does not reserve enough maintenance space, as shown in Figure 6a,c. Leakage is a common problem in SWH systems, as shown in Figure 6b. If collectors are installed on the roof, additional waterproofing of the roof is required.



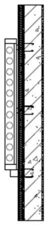
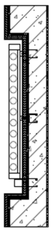
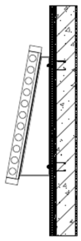
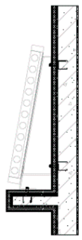
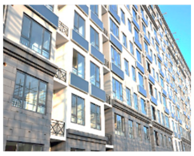
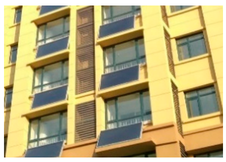
(**a**) No maintenance space (**b**) Collector leaking water and freezing (**c**) Collector is blocked

Figure 6. Common problems when installing solar collectors on roofs.

(2) Walls

Wall-mounted installation includes both vertical and inclined configurations as shown in Table 5. In terms of safety and efficiency, Type 4 is best for high-rise buildings. There is a great security risk for Type 1 and Type 3 installation modes. Type 2 is not conducive to the maintenance of the collector.

Table 5. Solar collectors installation modes on walls.

Types	Type 1: Attached	Type 2: Embedded	Type 3: Bracket	Type 4: Pallet
Sketches				
Installation mode	Attached to the wall	Embedded in the wall	Attached to the wall by a stainless-steel bracket	Supported by a pallet
Angle	0°	0°	15°	15°
Cases for FPCs				
Cases for ETCs				

Collectors also can be used as a fixture to the outer facing windows, as shown in Figure 7. This installation requires that the color of the glass is the same as the color of the absorber surface of the collector.

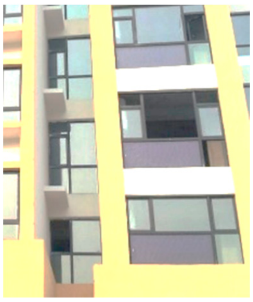


Figure 7. Collectors used as part of the outside windows.

For installation of solar collectors on walls, sufficient space should be guaranteed for ease of maintenance. The wrong installation method as shown in Figure 8a; once the collector fails, the parts cannot be replaced, eventually causing the equipment to lie idle. In order to save costs, the installation of Type 3 was widespread in China, which is an installation method containing significant security risks. If an uncertified stainless steel bracket is used or if a rivet is not driven to a sufficient depth in a wall, the collector would easily fall from a tall building, as shown in Figure 8b. At present, this type of installation has been gradually reduced, and Type 4 with a pre-designed platform has become popular.

(**a**) No maintenance space.

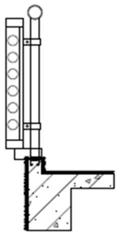
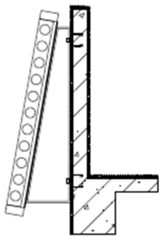
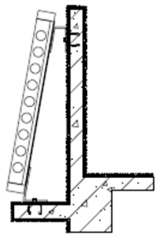
(**b**) Unqualified stainless-steel bracket rusts easily.

Figure 8. Common problems with wall-mounted installation.

(3) Balconies

Balcony-mounted installation also includes vertical and inclined configurations as shown in Table 6. There is a lower cost for vertical installation but these have lower system efficiency. The SWH system is more efficient while utilizing tilting installation, but it also requires higher material costs and careful design. A combination of collectors and railings is an excellent way to install solar collectors in high-rise buildings as shown in Type 1 of Table 6. This installation mode not only does not occupy additional space, but the collector can also replace the original railing, decreasing a portion of the material cost without affecting the original façade design of the building.

Table 6. Solar collector installation modes on balconies.

Types	Type 1: Attached	Type 2: Bracket	Type 3: Pallet
Sketches			
Installation mode	Integrated with balcony railings	Attached to balcony railings by a stainless-steel bracket	Attached and supported by a pallet
Angle	0°	15°	15°
Cases			

3.7. Auxiliary Heat Sources

Electric heating elements are the most common auxiliary heat sources for SWH systems. Electric heating elements account for 89% (32 projects) of all cases. Gas water heaters (GWH) or gas boilers (3 projects) and air source heat pumps (ASHP) (1 project) are also used as auxiliary heat sources. A comprehensive comparison of different types of auxiliary heat sources in individual household SWH systems is shown in Table 7.

Table 7. A comparison of different types of auxiliary heat sources in individual household SWH systems.

Heat Sources	Electric Heating Element	GWH or Gas Boiler	ASHP
Efficiency	70%	90%–107%	COP*, 2.5–3
Cost/Household	50–100 CNY	2500–6000 CNY	6000 CNY
Advantages	Space saving, a low initial investment	Instant heat when using, Low operating cost	Low operating cost
Disadvantages	High operating cost	The high initial investment, Needs installation space	The high initial investment, Requires a large installation space, noisy

* COP is an abbreviation of the coefficient of performance of a heat pump, which is a ratio of useful heating provided to work required.

From practical experience, compared with electric heating in hot water storage tanks, an "instant heat when using" GWH has a higher solar fraction and lower annual energy consumption. Liu Jian [62] conducted a test for a household SWH system in Shanghai with a 100 m^2 building area for different auxiliary heat sources and found that the solar fraction was increased by 45.4%, and the annual operating costs were reduced by 40.7% with a GWH compared to electric heating.

Due to the heat loss from water tanks, the auxiliary electric heating element consumes an abundance of energy to maintain constant water temperature in the water tank. This signifies that electric heating is inefficient. Although electric heating dominates the auxiliary heat source market for SWH systems at present, a GWH is recommended as the best choice for the auxiliary heat source for an

SWH system if there is adequate installation space. This is especially true due to its high reliability, high cost-effectiveness and increased convenience.

3.8. Economic Performance

By analyzing the 36 cases in different cities in China, the cost of SWH systems per m^2 of building area, including equipment expenses and the installation cost, is between 22 CNY/m^2 and 75 CNY/m^2 for different systems and collectors. The average cost is 45 CNY/m^2. With the soaring housing prices in Chinese cities over the past decade, the incremental cost from SWH systems accounts for only 0.1%–0.7% of the total housing price for different cities. In first-tier cities such as Beijing, Shanghai and Shenzhen, the incremental cost is lower than 0.2%. For developing cities such as Wuhan and Jiangxi, the incremental cost is lower than 0.7%. The average percentage of cost is 0.3%; it is acceptable for developers and residents when considering the energy cost savings from the renewable energy systems.

Although the initial investment of SWH system is higher than that of the other two types of water heaters (electric heating and gas water heaters), its annual actual energy consumption and yearly operating costs are relatively low, and the heating price is lower than that of the other heat sources. In the following section, the economic performance of individual household SWH systems will be analyzed in detail with a case study from Shanghai.

3.9. Operation and Maintenance

Insufficient hot water in winter, water leakage, and lack of professional operation and maintenance personnel are the three major problems in the operation of SWH systems. The survey found that only 43% of solar energy companies conduct operation and maintenance training for property management personnel, and 57% of solar energy companies do not provide operation and maintenance training.

4. Case Study

Sanxiang Haishang Cheng community is located on the south side of Changjiang West Road, Baoshan District, Shanghai. The project consists of seven 18-floor high-rise residential buildings with a height of 52.5 m; 23 multi-story residential buildings, and several commercial buildings for entertainment and other public uses. The project began construction in March 2010 and was completed in November 2013. Figure 9 shows the layout of the entire community and the location of the high-rise residential buildings.

There are 663 households in the seven high-rise residential buildings, in which, 524 households installed SWH systems. Compound parabolic solar collectors produced by Linuo-Paradigma Co. [63,64] were used in this project. The collectors were mounted on the outside of the apartment balconies with an area of 3 m^2. Each household was equipped with a heat storage tank with a volume of 150 L or 100 L, and a gas boiler as the auxiliary heat source with an output power of 24 kW. The designed solar fraction was 66% for the household with 150 L water tank according to the Technical Standard for Solar Water Heating System of Civil Buildings (GB 50364-2018) and the Assessment Code for Performance of Solar Water Heating Systems (GB/T 20095–2006) [65]. The system schematic is shown in Figure 10. The installation node diagrams are shown in Figure 11. Actual photos after the completion of the high-rise building and the SWH system are shown in Figure 12.

To evaluate the economic performance of the individual household SWH systems and compare the performance to EWHs, GWHs, and ASHP water heaters, the levelized cost of heat (LCoH) of different types of water heaters is calculated with Equation (7):

$$LCoH = \frac{I_o - S_o + \sum_{t=1}^{T} \frac{C_t}{(1+r)^t}}{\sum_{t=1}^{T} \frac{E_t}{(1+r)^t}} \quad (7)$$

where:

LCoH is the levelized cost of heat in CNY/kWh;
I_o is the initial investment in CNY;
S_o is subsidies and incentives in CNY;
C_t is operation and maintenance costs (year t) in CNY;
E_t is saved final energy (year t) in kWh;
r is the discount rate in %; The discount rate is defined as the weighted average cost of capital (WACC). According to the National Bureau of Statistics of China, 3% was used in the study. and
T is a period of analysis in the year. 15 was used for solar collectors and ASHPs, and 8 was used for gas boilers in the study.

Figure 9. The location of the high-rise residential buildings in Sanxiang Haishang Cheng community.

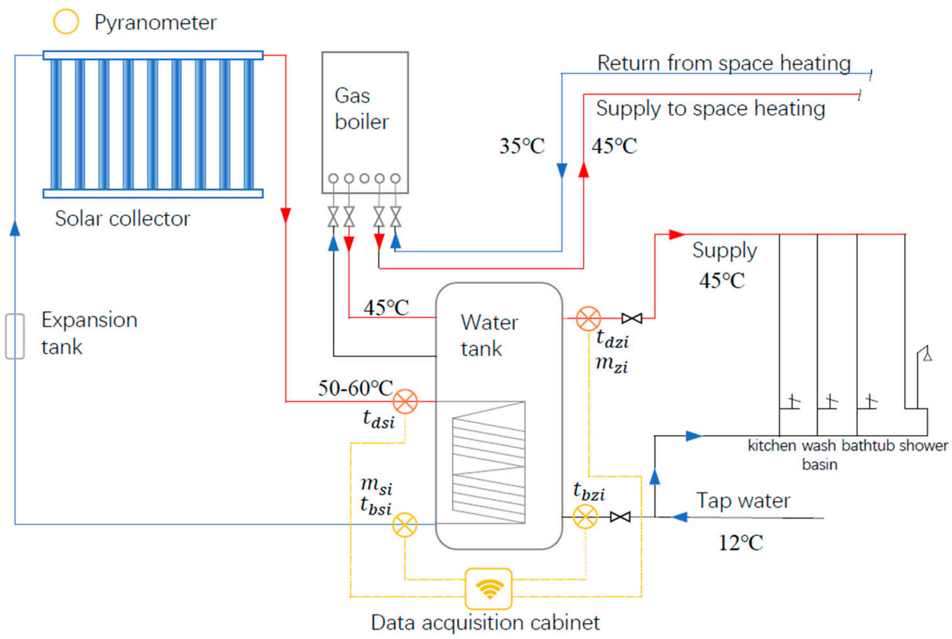
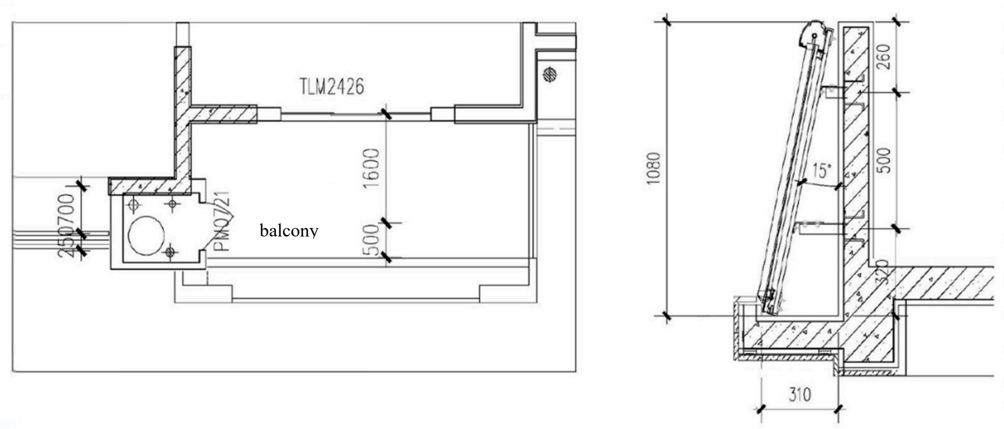
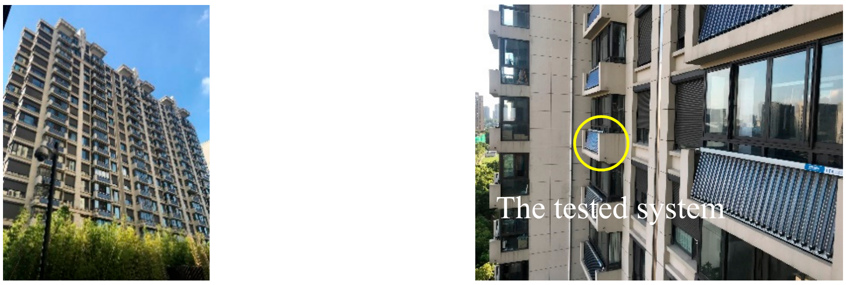


Figure 10. System schematic.



(**a**) Plan (**b**) Elevation

Figure 11. The diagram of the installation nodes.



(**a**) Building elevation (**b**) The tested system

Figure 12. Photos after completing the installation.

For the SWH system, the software PolySun is used to calculate the system efficiency, energy savings, and the solar fraction, with the assumptions listed in Table 8.

Table 8. A comparison of the levelized cost of heat (LCoH) for different water heaters with the SWH system for Shanghai Shanxiang project.

Types	Unit	SWH System	EWH	GWH	ASHP Water Heater
Power	kW	27[a]	2	27	0.8
Efficiency	%	60%[b]	70%	89%	COP, 3.4
Life span	years	15	8	6	15
Initial investment	CNY	7500 + 2500	1500	2500	6000
Subsidies	CNY	5400[c]	0	0	0
Energy price	CNY/m^3, CNY/ kWh	0 / 3.3	0.6	3.3	0.6
Operation cost	CNY/a	363	2190	960	451
Maintenance cost	CNY/a	300	100	200	200
LCoH	CNY/kWh	0.38	0.97	0.62	0.41

[a] Choosing a GWH as the auxiliary heat source. [b] The efficiency of solar collectors, in this case, choosing CPCs. [c] There is no subsidy for cities with a mandatory installation policy, but for some cities with incentive policies, such as in Shanghai, there are subsidies from local governments for the installation of SWH systems. In this case, the incremental cost from utilizing SWH systems is 10,000 CNY, which accounts for 0.1% of the house price.

The LCoH of the SWH system is calculated to be 0.38 CNY/kWh, which is the lowest in comparison to other types of water heaters. The lowest heat price shows the economic advantages of SWH systems in high-rise buildings.

To verify the system thermal performance and the real contribution from solar collectors, a field measurement was conducted for a typical household located in the middle level of 30# building (8th floor) as shown in Figures 9 and 12b. The annual solar fraction is calculated with Equation (4). The calculation was summarized in Table 9.

Table 9. The solar fraction (SF) field test and calculation for Shanghai Shanxiang project.

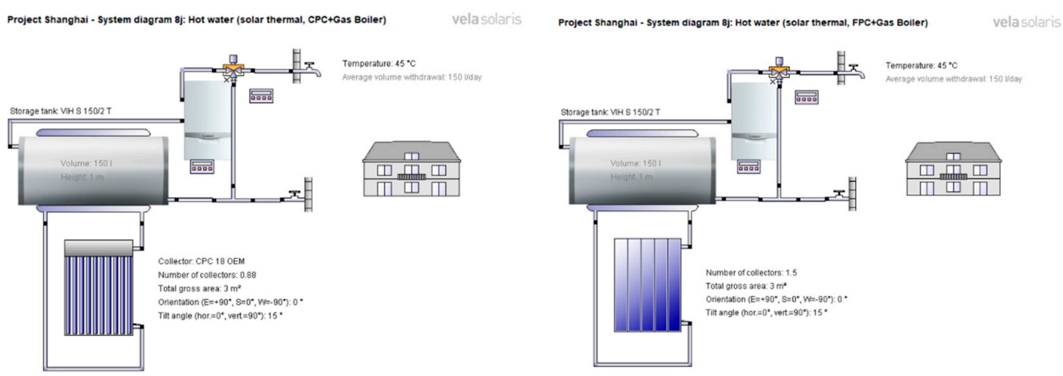
Test Items	**Total Solar Radiation on the Day**			
	R < 8	**8 ≤ R < 13**	**13 ≤ R < 18**	**R ≥ 18**
Days (x_1, x_2, x_3, x_4)	98	101	77	89
SF of the day (SF_1, SF_2, SF_3, SF_4)	15.5%	48.4%	72.4%	100%
The annual SF_{Annual} = 57.2%				

Table 9 shows that there is a difference between the tested annual solar fraction, 57.2%, and the design value of 66%. The difference is mainly due to the shading of the adjacent balcony, as shown in Figure 11b.

5. Discussion

5.1. Performance Comparison of Different Systems

Since there is a subsidy for the installation of SWHs in Shanghai, the owners chose the expensive CPCs to take advantage of their higher efficiency and the higher solar fraction. However, this is not a common practice. In high-rise buildings, FPCs are the most commonly used collectors. To compare the economic performance between FPCs and CPCs, the SF and LCoH values with different areas and types of collectors in the Shanghai Sanxiang case are calculated with the PolySun software. The PolySun models are shown in Figure 13 and the input parameters of the models are listed in Table 10.



(**a**) PolySun model for the CPC system (**b**) PolySun model for the FPC system

Figure 13. The PolySun model to calculate the solar fraction for CPCs and FPCs.

Table 10. The input parameters of the PolySun models.

Location	Shanghai
Weather data	Meteonorm weather data
Water tank volume	150 L
The output power of the gas boiler	24 kW
Supply temperature	45 °C
Collector area	3 m^2
Collector orientation	South
Collector tilt	15°

Results of the calculations are shown in Figures 14 and 15. Figure 14 shows that the annual SF of the CPC system is higher than that of the FPC system. When the installation area of collectors is 3 m^2, the annual SF of the CPC system is 0.67. For the FPC system, the SF is 0.58.

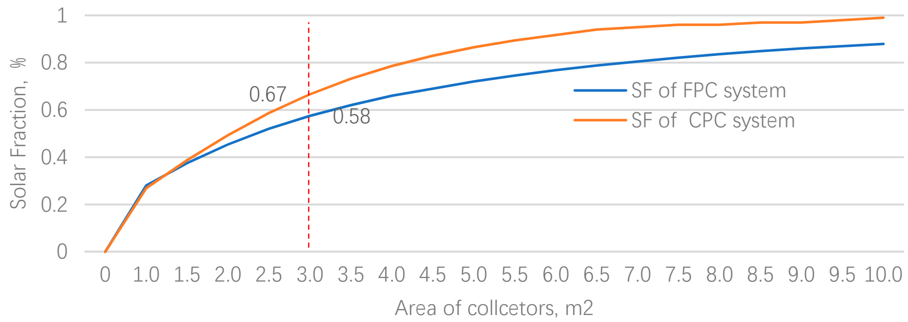


Figure 14. The solar fraction trend with the area (m^2) of CPC and FPC.

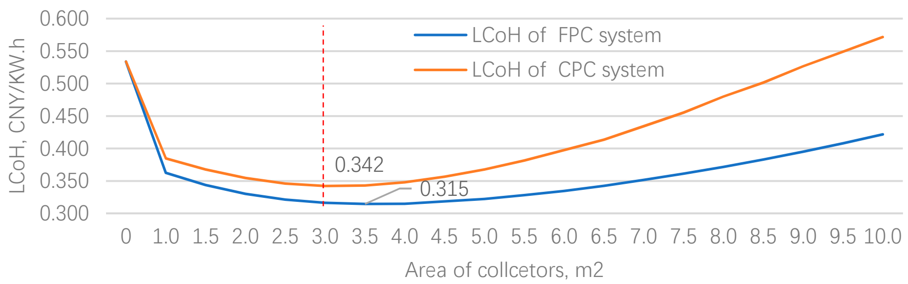


Figure 15. The LCoH curves with the area (m^2) of collectors with different types of collectors.

Figure 15 shows the economic performance of the two systems. The LCoH is lowest when the installation area of CPC reaches 3 m^2. The lowest LCoH for the system with FPC is achieved with a collector area of 3.5 m^2. Due to the limited space of the balcony, an increase in the collector area is impossible.

The comparison shows that the CPC system can harvest 16% more solar energy than the FPC system with a corresponding 7% increase of LCoH in this case.

Economic performance is also influenced by the auxiliary heat source. The LCoH curves with electric heating and a gas water heater as the auxiliary heat source for the CPC system are drawn in Figure 16. Figure 16 shows that when the solar collector area is less than 3 m^2, the LCoH of electric heating is higher than that of GWH. However, the LCoH of electric heating would be lower than that of GWH with a larger solar collector area. These calculations validate the rationale for the design in the Shanghai case.

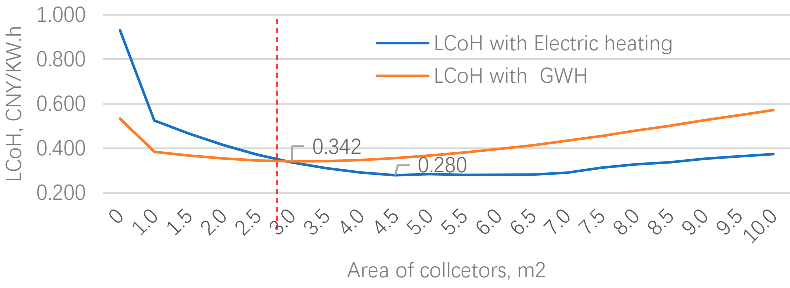


Figure 16. The LCoH curves with the area (m^2) of collectors with different auxiliary heat sources.

5.2. Limitations of this Study and Future Work

This study is based on the technical and economic analysis of China's experience in the application of SWH systems in high-rise buildings. Due to limited time and resources, it is impossible to investigate all SWH systems in high-rise buildings in China, which limits the geographic coverage of the study.

The collectors are limited to the types that have also been widely used. It can be seen from the comparison of various familiar collectors in Table 3 that the listed solar collectors are difficult to integrate with architectural design, due to their large size, considerable weight, and single color (usually black or blue). These factors affect the widespread use of solar heat in high-rise buildings. With the rise of building integrated photovoltaic (BIPV) [66–68] and air source heat pumps in recent years, the application of SWH systems in urban buildings is facing increasing challenges.

However, with technological innovation, there will be more collectors that can easily be integrated into building facades [69], e.g., a PV/T collector that can generate heat and electricity [57], solar thermal air collectors, ceramic solar collectors, polymer solar collectors and solar louvre collectors that can be integrated into curtain walls.

6. Conclusions

The experiences and lessons of SWH system applications in high-rise buildings are summarized based on the investigation of 36 existing SWH systems in high-rise buildings in China. The economic performance of SWH systems in high-rise buildings is analyzed and verified by a case study in Shanghai. The following conclusions can be drawn:

1. The installation of SWH systems in high-rise buildings is feasible and reliable with careful design, construction, operation and maintenance. Insufficient hot water in winter (29%), water leakage (21%), lack of professional operation and maintenance personnel (10%) are the three major problems in the operation of SWH systems.
2. Mutual occlusion between buildings will significantly reduce the efficiency of SWH systems. Usually, the aperture area of the collector is half-blocked, and the energy consumption of the auxiliary heat source is correspondingly doubled.
3. An individual household system (61%) is better than a centralized system (25%) in high-rise buildings in terms of the system efficiency, higher solar fraction for single households, and assurance of the installation area for solar collectors.
4. The average area of solar collectors per household was 2.17 m^2/household, the average design solar fraction was 52%.
5. FPCs are most suitable for the integration with SWH systems in high-rise buildings in terms of system security and reliability. However, when considering the system efficiency, CPCs are better with higher SFs, but the installation of CPC in high-rise buildings requires strict supervision and reliable technical support to ensure safety and security. The system requires fewer CPCs, compared to FPCs, to reach the lowest LCoH.
6. When solar collectors are installed on roofs, a floating board is the best installation method to integrate solar collectors with roofs to ensure adequate installation space and minimize the impact

on the architectural design. If solar collectors have to be installed on walls, a pallet should be designed to support collectors. Wind loads need to be considered during the structural design of the pallet.

7. Electric heating elements (89%) were the most common auxiliary heat sources for SWH systems, followed by gas water heaters and air source heat pumps.
8. The cost of SWH systems per m^2 of a building area, including the equipment expense and the installation fees, was between 22 CNY/m^2 to 75 CNY/m^2. The average percentage was 0.3% of the total building construction cost; it is acceptable for developers and residents when considering the energy cost savings from solar thermal.

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Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

AGETC	All-glass evacuated tubular solar collector
ASHP	Air source heat pump
BIST	Building integrated solar thermal
CNY	Chinese Yuan
CPC	A compound parabolic collector with a U-shaped copper pipe inside
ETC	Evacuated tubular collector
EWH	Electric water heater
FPC	Flat plate collector
GWH	Gas water heater
HPETC	An evacuated tubular collector with a heat pipe inside
LCoH	Levelized cost of heat
SF	Solar fraction
SWH	Solar water heating
UPETC	An evacuated tubular collector with a U-shaped copper pipe inside
Symbols	
A	the gross area of the solar collector, m^2
a_1	the heat loss coefficient of a collector at ambient temperature, W/(m^2K)
a_2	the temperature dependence of the heat loss coefficient of a collector, W/(m^2K^2)
C_t	operation and maintenance costs (year t), CNY
c_w	the specific heat capacity of water, J/(kg·K)
c_{sw}	the specific heat capacity of a collector fluid, J/(kg·K)
E_t	the saved final energy (in year t), kWh
f_j	the solar fraction obtained in short-term tests under specific solar radiation conditions, %
f	the calculated annual solar fraction of the system, %
G	the solar irradiance on the collector, W/m^2
I_0	the initial investment, CNY
$k\theta$	the incidence angle modifier
m_{zi}	the hot water flow rate recorded in i-th test, m^3/s
m_{si}	the working fluid flow rate in the heat collection system recorded in i-th test, m^3/s
Q_z	the total energy consumption of the solar water heating system, MJ
Q_s	the total heat gain of solar collectors, MJ
r	the discount rate, %
S_0	subsidies and incentives, CNY

T	the period of analysis, year
t_{dzi}	the hot water temperature recorded in i-th test, °C
t_{bzi}	the cold water temperature recorded in i-th test, °C
t_{dsi}	the collector fluid temperature at the outlet recorded in i-th test, °C
t_{bsi}	the collector fluid temperature at the inlet recorded in i-th test, °C
ΔT_{zi}	the time step, s
ΔT_{si}	the time step, s
η_0	the peak collector efficiency
θ	the incidence angle for radiation, °
ρ_w	the density of hot water, kg/m^3
ρ_{sw}	the density of collector fluid, kg/m^3

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