Classifications of central solar domestic hot water systems

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Abstract. Currently, there are many means by which to classify solar domestic hot water systems, which are often categorized according to their scope of supply, solar collector positions, and type of heat storage tank. However, the lack of systematic and scientific classification as well as the general disregard of the thermal performance of the auxiliary heat source is important to DHW systems. Thus, the primary focus of this paper is to determine a classification system for solar domestic hot water systems based on the positions of the solar collector and auxiliary heating device, both respectively and in combination. Field-testing data regarding many central solar DHW systems demonstrates that the position of the auxiliary heat source clearly reflects the operational energy consumption. The consumption of collective auxiliary heating hot water system is much higher than individual auxiliary heating hot water system. In addition, costs are significantly reduced by the separation of the heat storage tank and the auxiliary heating device.

1. Introduction

Solar energy resources are rich within China; more than two-thirds of the country receives at least 2,500 hours of sunshine each year, creating advantageous conditions for the development and utilization of solar energy. Currently solar energy heat utilization is used primarily for the supply of hot water for domestic purposes, which accounts for more than 90% of solar energy heat utilization in China [1]. Nevertheless, many challenges persist in the application of solar hot water systems in residential buildings. For example, the high price of the adaptive technology can be prohibitive [2]. The cost of hot water supply for 144 residents in Henan, Yunnan, Beijing, Guangdong, Shandong and other places was investigated. Results indicated average costs which exceed 20 yuan/ton, accounting for 18% of the survey samples. Unfortunately, energy management contracts require a price of 40-60 yuan/ton, which greatly exceeds the cost of electric water heaters. In addition, property management companies report great challenges, including high maintenance costs and difficult management of DHW systems [3]. Existing studies have primarily focused on solar collector efficiency, rather than system level analysis. Some researchers have reported the impact of energy consumption of the different systems. Suzhen Lu investigated numerous applications of central solar domestic hot water systems, and suggested that system form has great influence on energy consumption [4]. Rui Yu, et al.,

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simulated the energy consumption of various systems in order to investigate their varying suitability [5]. Some researchers have suggested that both heating methods and heating devices represent core components of hot water supply systems [6, 7]. Liuxiang Zhang, et al., investigated the basic system characteristics in detail which, combined with appropriate technology, can be used in central solar domestic hot water systems [8]. These studies all indicate that the system form has a significant impact on practical applications.

The key to popularization and the reform of technical standards is to develop a system of classification for solar hot water systems. Foreign standards primarily refer to the international standard ISO 9459-2-1995, which is categorized according to the seven features of solar hot water systems: the relationship between solar energy and other energy sources in the system, whether the heat transfer medium in collectors can be applied directly to users, whether the heat transfer medium comes in contact with air, etc. Each of the seven characteristics is divided into 2-3 types, allowing the classification of a wide range of solar hot water systems.

Existing classifications in China are primarily derived from provisions within the international standard, including the following: <Technical code for solar water heating system> (GB50364-2005), <Solar-plus-supplementary water heating system> (GB/T29158-2012), <Guide of Engineering Testing of Construction Solar Water Heating System> (GB/T20095-2006), etc. Various standards employ different methods of classification. For example, <Technical code for solar water heating system > (GB50364-2005) suggests that classification is based on the scope of the hot-water supply, system operation mode, heat transfer medium in the collector and auxiliary heat source at the installation point, and start mode. There are many additional methods of classification. For example, according to the type of solar collectors employed, systems can be divided into numerous categories including flat solar, vacuum tube, or u-tube solar hot water systems; according to the volume of the storage tank, systems can be divided into solar water heaters with a tank capacity of less than 0.6m$^3$, and those with a tank volume that is equal to or greater than 0.6m$^3$.

The <Technical code for solar water heating system> (GB50364-2005) clearly indicates that the design of a solar hot water system should be primarily equipped according to the building water supply and available drainage, in accordance with the requirements of the <code for design of building water supply and drainage> (GB50015-2003). Experience will also simultaneously serve as the primary basis of expert design.

Above all, the emphasis of previous research on water characteristics and the solar collection system are not conducive to the design and operation of central solar domestic hot water systems. Therefore, the incorporation of the thermal performance of solar hot water systems is necessary to promote their development and practical application. Future research should also incorporate the household load when designing solar collection systems.

2. Thermal performance in solar hot water systems

Classification methods must take the nature of the solar hot water system into account. As previously discussed, solar hot water systems are comprehensive, and are comprised of three features: heat, energy and water. The thermal performance must also be taken into account, which reflects the thermal energy storage and heating capacity of the auxiliary heat source.

Due to thermal energy storage and regulations, the performance of the heat storage tank directly affects the operation of the entire system [12]. The heat storage tank stores heat collected during the day for use in the evening; the water temperature in the heat storage tank is approximately 50°C or more. The relationship between the volume of the tank, the area of the solar panels and user water consumption should also be taken into account. Due to the instability of solar heating, an auxiliary heat source is typically included in the system. The primary function of the auxiliary heat source is to produce hot water when heat consumption is greater or the amount of available hot water has been reduced (i.e., as a result of bad weather). Without an auxiliary heat source, the system will not function properly. In terms of heat, solar hot water systems consist of collected solar energy and
heat provided by the auxiliary heat source, which are affected by user consumption and heat dissipation.

During system operation, water reflects heat flow as the medium flows through the system (Figure 1). Results indicated that solar energy cannot be efficiently distributed to the user in many applications. It can be assumed that heat provided by solar energy is 100 (GJ); however, due to the efficiency of solar collectors, only 40% of solar energy can actually be supplied. As the heat flows into the heat storage tank, approximately only 70-80% of collected heat is retained. Investigation and field-testing of central solar hot water system projects in Beijing, Inner Mongolia and Tianjin, indicated approximately 70% of collected heat is lost.

![Figure 1. The energy flow schematic diagram of solar domestic hot water systems.](image)

Therefore, it can be concluded that much solar energy is lost before it is distributed to the user, necessitating the inclusion of an auxiliary heat source. Thus, it is possible to evaluate the performance of a solar hot water system according to the consumption of the auxiliary heat source, which is an important system factor.

3. Analysis the problem of classification

At present, DHW systems are primarily classified according to the building water supply and drainage, while the energy supply is rarely taken into account. For example, according to the <Technical code for solar water heating system of civil buildings> (GB503642005), classification of the scope of hot water supply can be divided into three forms, as presented in Table 1.

| No.  | System                              | Solar collector | Heat storage tank |
|------|-------------------------------------|-----------------|-------------------|
| 2.0.10 | Collective hot water system       | Central         | Central           |
| 2.0.11 | Collective-individual hot water system | Central         | Individual        |
| 2.0.12 | Individual hot water system       | Individual      | Individual        |

As shown in Table 1, this method of classification considers the features of solar energy collection and water use, but does not take into account the thermal energy storage and the auxiliary heat source, which are indispensable in the system. Specifically, solar energy provides the heat accumulated throughout the entire day; however, it is impossible to satisfy the hot water requirements of every day throughout the year using solar power alone. Therefore, the auxiliary heat source is necessary to meet hot water demand, and which reflects the thermal performance of the heating action. Without heat storage, the collected heat would be lost, and which reflects the thermal performance of thermal energy storage.

3.1 Analysis the problem of classification

Ignoring the influence of the auxiliary heat source within the system may not reflect the thermal performance of the solar hot water system, complicating the existing classification methods. A solar fraction is typically used to evaluate the performance of solar hot water systems, which rely on the heat collected from solar energy to ensure that heat demands are met. Therefore, the influence of the auxiliary heating device in the system must be taken into account.

The primary concern of residents when evaluating choices of hot water systems is the cost of the hot water supply, which includes the price of water, management expenses, operation, maintenance, replacement parts, etc. Xiaohui Du reported that the high prices associated with some residential
buildings discouraged some residents from use of their hot water systems. Meanwhile, this burden also exists for developers, property owners and property management companies.

Cost primarily reflects the consumption of auxiliary conventional energy [21]. As demonstrated by typical values, regardless of geography and with the exception of fixed costs (such as construction costs and the price of water), the greatest cost variable is the consumption of auxiliary conventional energy, i.e., water or gas.

According to the <Code for design of building water supply and drainage>, the solar fraction can be calculated by the following equation according to the heat collected and the total load:

\[ f = \frac{Q_s}{Q} \]  

(1)

Some researchers have reported that this indicator alone cannot appropriately describe the system. In order to address this problem, the indicators of solar availability and auxiliary conventional energy substitution rate have been developed, as determined by the following equation [11, 13, 16]:

\[ f_s = \frac{Q_s - Q_d}{Q_s} \]  

(2)

\[ f_a = \frac{Q_s - Q_u}{Q_s} \]  

(3)

Field-testing of many projects with different system forms indicated a relationship between hot water cost and various indictors (Table 2).

**Table 2.** Relationship between hot water cost and evaluation indicators.

| System  | Project | Solar fraction | Price (yuan/ton) | Solar availability | Auxiliary conventional energy substitution rate |
|---------|---------|----------------|-----------------|-------------------|-----------------------------------------------|
| Central | Beijing | 100%           | 25              | 6.2%              | 18%                                           |
|         | Chifeng | 89%            | 20              | 21%               | 19%                                           |
| Individual | Tianjin | 79%            | 15              | 32%               | 25%                                           |

As shown in Table 2, the solar fraction of central hot water systems is less than that of individual hot water systems. In accordance with the original project evaluation, high solar fractions indicate not only high conventional energy substitution rates, but also indicate overall good system performance. However, the price of hot water remains high due to the greater use of auxiliary conventional energy and the lesser contribution of solar energy to the system, which is demonstrated by the auxiliary conventional energy substitution rate. As a result, a solar fraction based only on the evaluation index cannot accurately evaluate the overall system performance, indicating that the consumption of auxiliary heat and hot water price should also be taken into consideration.

Present methods of classification take into account only the solar energy, while neglecting the auxiliary heat source. Due to underestimation of the contribution by the auxiliary heat source in system specification and design, many projects have been developed which have high solar fractions but fail to conserve energy. Therefore, this paper proposes that consumption of the auxiliary heat source should be used as the primary basis for the evaluation of energy saving systems.

3.2 Influence of heat features

Classification methods often take into account the water features, but neglect the influence of heat, resulting in the current research trend which focuses primarily on water conservation in solar domestic hot water systems. Systems with heat features supply not only the water but also the heat, which must also take into account any heat lost in transfer. Some researchers have reported that heat loss accounts for more than 30% of the total heat included in the system. Ignoring the hot feature of philosophy would lead to the non-energy saving design. Therefore, the present classification methods cannot provide accurate and scientific classification of solar energy heat water systems.
4. Categorization of systems by auxiliary heat source position

Based on the discussion above, scientific classification of domestic solar hot water systems should take thermal performance into account. Thus, the position of the heat storage tank, auxiliary heating device, and the the centralized or individual nature of the system, should be considered in the classifications of the central solar hot water systems. This section introduces a classification principle based on the position of the auxiliary heat source rather than the tank capacity, which differs from the principle offered in <Technical code for solar water heating system of civil buildings> (GB503642005) and other standards.

4.1 Position and energy consumption

Guangwei Deng compared collective hot water systems and individual hot water systems, and determined that 24-hour supply introduced enormous heat transmission and distribution losses, and substantially increased costs in the system [9]. Rui Yu, et al., applied the model to analysis of collective hot water systems, and reported that consumption by individual auxiliary heat systems was far less that consumption by collective auxiliary heating systems [6]. By analyzing data from multiple solar hot water system projects, results indicate that the position of the auxiliary heat source has great influence on the energy consumption. In order to analyze and compare solar energy collection, Heat dissipation and Heat of auxiliary heat source, bench marking in user heat which sets 100 and the 4 parts were standardized. As we know, the size of the system would lead to the different hot water demands. So, by this way, we can see consumption of heat clear. The results are shown in Table 4.

Table 4. Various system parameters.

| System                        | Position     | Type       | Supply time | Project   | Solar energy collection | Heat of auxiliary heat source | Heat dissipation | Hot water cost (yuan/t on) |
|-------------------------------|--------------|------------|-------------|-----------|-------------------------|-----------------------------|-----------------|---------------------------|
| Collective hot water system   | Collective  | Electric   | All day     | Beijing   | 295                     | 82                          | 277             | 25                        |
| Individual hot water system   | Individual  | Electric   | Fixed time  | Chifeng   | 100                     | 79                          | 79              | 20                        |
|                               |              |            | All day     | Tianjin   | 41                      | 71                          | 12              | 15                        |

In terms of heat dissipation, an all-day hot water supply system in Beijing and Tianjin was compared to a collective auxiliary heating system with maximum heat loss. Based on the amount of heat dissipation, results indicate that solar energy is almost entirely lost, which prohibits residents from taking full advantage of their heating systems. The Tianjin project investigated the characteristics of an individual auxiliary heating system whose heat dissipation accounted for 12% of all collected heat, indicating that nearly all collected heat flowed to the residents. In general the energy consumed by all-day hot water supply systems is greater than consumed by fixed-time hot water supply systems. Due to the enormous heat dissipation experienced by all-day systems, the hot water supply system must employ the auxiliary heating device to guarantee that hot water demands can be met at any time, whereas fixed-time hot water supply systems can only provide hot water during the time allotted [11]. The heat loss of the Chifeng project is much greater than that of the Tianjin project, as related to supply time and auxiliary heat source position. For central solar hot water systems, the heat dissipation in the collective auxiliary heating system is greater than that of individual auxiliary heating systems. The location of the auxiliary heating device in the tank, heat loss in the pipe loop provided by the
auxiliary heat source is avoided, resulting in a heat loss ratio less than that of collective auxiliary heating hot water systems.

In order to elaborate on the principle of classification, another system known as an instantaneous solar domestic hot water system is described below (Figure 2).

![Figure 2. Collective heat collection and individual auxiliary heating solar hot water supply system.](image)

According to the position of the auxiliary heating device, the above system is an individual auxiliary heating system. This system differs from the collective hot water system, which can be defined in relevant codes, due to the position of the tank.

Advantages of this model include cost reduction and increased ease of application. When the auxiliary heating device and heat storage tank are provided in combination, heat must be constantly provided by the auxiliary source to ensure the water temperature in the tank. This system uses heat from an auxiliary heat source to guarantee that needs are met rather than relying on solar energy collection, in order to reduce heat dissipation during delivery. Wang Guojian compared the various forms of solar domestic hot water systems, and determined that the above system (which is supplemented by gas) provides an annual coal consumption of approximately 37% as compared to electric auxiliary heating systems. Additionally, the above system can effectively reduce the initial investment cost and hot water cost to approximately 8.5 yuan/ton [15]. In regard to energy conservation and investment and user experience, this system has promising applications for the future development of central domestic solar hot water systems.

Based on analysis of heat loss and heat provided by the auxiliary heat source in the above system, it can be concluded that the position of the auxiliary heating device as collective or individual greatly influences system consumption.

4.2 Position and user demands

- Occupancy rate

High occupancy residential buildings are suitable for collective-individual hot water systems [17]. When the heat consumption is small, effective utilization is realized. If the users bear all associated costs, the final price will be prohibitive. In order to ensure a sufficient number of
users, the property company which operates the system at low cost will apply winter heating profits to compensate for the loss of hot water systems, inflicting heavy losses on both users and property owners.

- **Operation and maintenance**
  Hot water requirements cannot be guaranteed in the case of failure. As compared to individual auxiliary heating systems, collective auxiliary heating systems are typically maintained by property management, who guarantees the system operation. In order to make the system user-friendly and easy to troubleshoot, users must incur initial investment expenses. When the efficiency is low, the operational cost may even exceed that of individual auxiliary heating systems.

- **User control**
  The operation and maintenance of individual auxiliary heating systems are inconvenient; however, they offer the advantage of flexible control. According to actual heat consumed per household, expenses can be more accurately arranged. In the event of bad weather, heating and time needs change depending on the needs of individual households. In addition, property charges for water and electricity costs become unnecessary, thus simplifying the management mode.

5. **Definitions**

Through discussion of the system forms, energy consumption and user requirements, this essay recommends categorization of heating systems according to the positions of the auxiliary heating device and solar collector, which serve as criterion to distinguish whether the system is a collective or individual system. There are two types of collective heat collection systems: collective auxiliary heating, individual auxiliary heating. Thus, the following definitions are proposed:

Collective heat collection-collective auxiliary heating hot water system which refers to the integration of a solar collector, heat storage tank, auxiliary heating devices, and unified installation which is assigned to a water supply the solar hot water to each terminal. The schematic diagram of a collective heat collection-collective auxiliary heating hot water system is shown in Figure 3.

![Figure 3. Schematic diagram of collective heat collection-collective auxiliary heating hot water system.](image-url)
A collective heat collection-individual auxiliary heating hot water system refers to a system with a solar collector installed in the roof in addition to numerous other devices set independently for each user, which include a heat storage tank and auxiliary heating devices. The schematic diagram of a collective heat collection-individual auxiliary heating hot water system is shown in Figure 4.

![Figure 4. Collective heat collection-individual auxiliary heating solar hot water system.](image)

6. Conclusions
Through the analysis of existing classification challenges, results indicate that the thermal performance of solar hot water systems have been largely ignored in previous research. Thus, to make the system of classification more scientific, the inclusion of thermal performance criteria in classification is proposed. For the classification of central solar domestic hot water systems, it is recommended that the position of the auxiliary heat source be located rather than in the storage tank, as recommended by *Technical code for solar water heating system of civil buildings* (GB50364:2005).

Alternatively, results indicate that different auxiliary heat source positions will greatly influence energy consumption and related costs. Therefore, for the development of central solar domestic hot water systems, collective heat collection-individual auxiliary heating solar hot water systems should be encouraged for wide application. Additionally, the separation of the heat storage tank from terminal auxiliary heating should also be promoted.

A. 1 Nomenclature

| Symbol | Description                  |
|--------|------------------------------|
| $f$    | Solar fraction (%)           |
| $f_s$  | Solar availability (%)       |
| $f_a$  | Auxiliary conventional energy substitution rate (%) |
| $Q_s$  | Solar energy collection (GJ) |
| $Q$    | System load (GJ)             |
| $Q_d$  | Heat dissipation (GJ)        |
| $Q_u$  | Heat of auxiliary heat source (GJ) |

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