Analysis for common problems in solar domestic hot water system field-testing in China

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Abstract

China's total urban solar thermal application area has gone up to 2.7 billion square meters by the end of 2013. Domestic solar hot water system, as a main form of solar thermal applications in the building sector, is widely used by city residents. It can substitute conventional energy and meet the residents' need of domestic hot water,. But how is the practical effect? To get the real results, it needs field-testing or monitoring. In China, field-testing is most common used. At present, through analyzing a large number of actual test data, we discovered that there are some common problems about the indicators and methodologies used in the field-testing. Some indicators do not reflect the purpose of the energy-saving design. Some test data deviates from the normal range of value. After communicated with several large organizations, we identified some difficulties in the actual field-testing, especially some data is hard to monitor. In order to better represent building energy efficiency, and fully address the ability of renewable energy substituting conventional energy, this article make an in-depth analysis of common problems occurred in solar domestic hot water system field-testing to identify shortcomings based on existing data. The final goal is to identify more effective system field-testing indicators and methods to better reflect the actual results and evaluate solar domestic hot water systems.

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1. Introduction

Solar energy could replace conventional energy to make alternative solutions for hot water needs of the people, making the solar domestic hot water system as the main form of light to heat application in buildings. The application scale has been gradually expanded. By the end of 2013, China's urban solar thermal applications floor area has been up to approximately 2.7 billion square meters. The solar collector area is about 300 million square meters.

Back in 2006, the Shenzhen Municipal makes simulation on solar illumination conditions according to their geographical latitude, the sun elevation angle, etc., drawing about the conclusion that the 12-storey residential building can basically meet the basic requirements of solar illumination condition. Then the Shenzhen Municipal promulgated the "Shenzhen Special Economic Zone Building Energy Conservation Ordinance ", for the first time making mandatory policy that 12-storey new building must be designed and installed the solar thermal system. After that most of other provinces follow it. Hainan, Zhejiang, Hebei, Jiangsu, Shanxi, Hubei, Ningxia, Shandong provinces also make mandatory policy that 12-storey new building must be designed and installed solar thermal systems. With the progress of the national urbanization to accelerate, balcony solar hot water systems gradually come into high-rise buildings market. Qinghai, Wuhan provinces began to try to force the 18-storey new buildings follow the installation[1]. Jinan city in Shandong recently promulgated the policy which requires 100 meters and below buildings to design and install solar thermal systems. With the "The Twelfth Five" is approaching the end, Beijing requires all new buildings in the urban-rural region regardless of building height to be designed and installed solar thermal systems, whose construction drawing should be reviewed. Solar hot water system mandatory policy is expanding in the geographical scope.

According to the relevant evaluation standard, solar fraction ratio is the formulary evaluation indicator of solar domestic hot water systems. The reference indicators for the evaluation, for example, conventional energy substitution volume, project cost-effective, environmental and economic benefit, also depend on the solar fraction ratio. The solar fraction ratio is a very important indicator, not only is the system design parameter, but also is the base to calculate conventional energy substitution volume and other indicators. In actual project evaluation, how can solar fraction reflect the system operating performance? Calculation of the conventional energy substitution volume is scientifically accurate? How is the system field-testing operability? Based on test data of Chinese solar domestic hot water system, this paper makes in-depth analysis with the aim to point out deficiencies, bring about more effective indicators and methods to evaluate solar domestic hot water system.

2. Solar hot water system testing method

According to the standard <Evaluation standard for application of renewable energy in buildings>, solar hot water system tests should be tested after running at least 3 days after installation and commissioning. Some requirements during the testing is as follows: the average ambient temperature is at the range from 8 °C to 39 °C. average flow rate of the ambient air is not more than 4m/s. Solar radiation at least four days should be in the following four sections: J1<8MJ/m2•day, 8MJ/m2•day≤J2<13MJ/m2•day, 13MJ/m2•day≤J3<18MJ/m2•day, J4 ≥18MJ/m2•day [2].

2.1. Testing and assessment content

Testing and assessment content includes testing indicators and calculating ones. Testing indicators include inlet temperature, outlet temperature and flow rate for heat collector system, ambient temperature, ambient air flow. Indicators to be calculated include the collecting heat from solar heat collector \(Q_c\), conventional energy consumption \(Q_{fz}\), hot water storage tank heat loss coefficient, the solar collector system efficiency (\(\eta\)), solar fraction ratio (f), the amount of conventional energy substitution volume (tce), the project cost-effective. What is needed to be evaluated by calculating is: environmental benefit, economic benefit and demonstration spreading effect.
2.2. Calculation method

2.2.1 The collecting heat from solar heat collector \((Q_c)\)

\[
Q_c = Q_v + Q_G
\]  

(1)

Where, \(Q_v\)-- Heat of hot water storage tank, MJ;  
\(Q_G\)-- Actual hot water heat consumption, MJ;

\[
Q_v = \rho_w \cdot C_w \cdot V_s \cdot (t_e - t_b)
\]  

(2)

In the formula,

\(\rho_w\)--Density of water at room temperature, kg/m³;  
\(C_w\)-- Heat capacity of water, J/(kg · °C);  
\(V_s\)--Volume of hot water storage tank, m³;  
\(t_e\)-- Final temperature of hot water storage tank, °C;  
\(t_b\)-- Initial temperature of hot water storage tank, °C;

2.2.2 Conventional energy consumption \((Q_{fa})\)

\[
Q_{fa} = Q_T - Q_C
\]  

(3)

In the formula,

\(Q_T\)-- Heat quantity that system should provide to users, namely the system design load, MJ; consists of the following three parts:

1. Actual hot water heat quantity \((Q_G)\);  
2. The heat quantity of supplementary heating water to 50 °C\((Q_A)\);  
3. In order to meet the design requirements, the other heat quantity \((Q_S)\);

2.2.3 The collector system efficiency \((\eta)\)

\[
\eta = \frac{Q_C}{A \cdot H}
\]  

(4)

Where, \(\eta\)-- Collector system efficiency,%;  
\(A\)-- Solar collector lighting area, m²;  
\(H\)-- Solar irradiance, MJ/m²;

2.2.4 Solar fraction ratio \((f)\)

\[
f = \frac{Q_c}{Q_T}
\]  

(5)

3. Common problems in solar domestic hot water systems field-testing

Before there have been articles which study the relative system testing problems. Liao Chunbo etc studied split solar hot water system thermal performance in Hangzhou, in which they found that some system is with high heat collector efficiency, the solar fraction ratio is very low [3]. Another, in some projects there is unreasonable calculation which calculates conventional energy substitution volume by daily useful heat gain[4].

In the process of analyzing the testing data of existed solar hot water system in residential buildings, there are a total of 47 projects, involving 72 systems, 258 day test data. But after further screening, there are 16 projects cannot be made in-depth and detailed analysis, due to the number of households and persons of the system is unknown.
There left only effective 31 projects, 56 systems and 209 day test data.

According to the analysis, in actual solar hot water system operating of residential buildings, there are some appearance such as larger amount of conventional energy, price higher than the electric hot water price and so on. One reason is that control system is imperfect and thus results in unlimited open of circulating pump. Secondly, the design load is too large that excessive auxiliary energy is used for hot water heating beyond the actual load. Next, I will analyze the existing test data and conclude several issues reflected by the test data.

3.1. System description is not detailed enough

When selecting the data from field-testing report for analyzing, there are some data cannot be used. Because that here is no description of the users of solar hot water system leading to uncertainty of actual hot water using volume. Solar hot water system has strong geographical features and characters as it is tightly connected with the users' purpose of the hot water and their habits. In order to better evaluate the solar hot water system, as the authoritative source of data, the testing report should be as detailed as possible.

Through collecting the data, we found that the system description should contain at least the following three key factors: First, the condition of the environment where the system is tested, including local solar energy resources of during the testing period, climate condition and the local hot water using habits. Second, the introduction of the system itself, including the system application form, system design parameters, selection of the products and the controlling mode of the collector system. Third, detailed introduction of hot water supplies, including the number of users, specifically the end distribution. Details are showed in table 1.

<table>
<thead>
<tr>
<th>Classification</th>
<th>Key Factors</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>System environment</td>
<td>Local solar radiation, day light per day, climate condition, local hot water using habits</td>
<td>System evaluation</td>
</tr>
<tr>
<td>System itself</td>
<td>System form, design parameters, selection of the products, control mode</td>
<td>Technical index, system evaluation</td>
</tr>
<tr>
<td>Hot water supplies</td>
<td>users' info, numbers, distribution</td>
<td>Water design volume, system evaluation</td>
</tr>
</tbody>
</table>

3.2. Testing time is inconsistent with actual condition

The test for solar hot water system is required after the construction is finished. But because the solar hot water system is largely affected by occupancy, the testing results would not reflect the actual condition. In order to meet the water heating load, the normal way is to drain off the water, which cannot reflect the real water demand.

It also can be seen from the existing test data that the average amount of hot water consumption is 52L/person/day, which is around the same as the design volume but very different from the actual condition. This is because we drained off the water in the test. We hope this problem can be resolved in the near future.

3.3. Testing method is inconsistent with the actual condition

According to the relevant evaluation criteria, one of solar water system testing requirements is that there should be at least 4 days in which daily accumulated radiation is in the distribution of following four sections: J1 <8MJ / m²•day, 8MJ / m²•day ≤J2 <13MJ / m²•day, 13MJ / m²•day ≤J3 <18MJ / m²•day, J4≥18 m²•day.

In the testing process, it is difficult to meet the requirements of the weather condition. Then what shall we do? In order to meet the radiation requirements, usually the testing time is counted from the beginning until the time when it meets the requirement. For example, when requiring the daily accumulated radiation less than 8MJ / m²•day, the testing time started from the beginning to the time when the accumulative number reach8MJ. The duration may be more than 8 hours, and also may be less than 1 hour.

As stated in the standard < Solar Hot Water System Performance Evaluation Standards > (GB / T 20095-2006), heating performance test of solar hot water system should meet the following requirements: For solar collectors placed facing south, southeast, and south west, if the testing duration meets 8 hours, daily solar radiation
should be larger than 17MJ/m². For solar collectors facing south east, south west, east, and west, and the testing duration is less than 8h test time, four hours before and after noon, the amount of solar radiation from the south direction and the solar collectors should be both greater than or equal to 17MJ/m². The starting and ending time is as follows: When the solar collector is facing south, for natural circulation and forced circulation system, testing time begin 4h before noon and end 4h after noon, with a total of 8 hours; For direct-current systems, testing time begins 4h before noon and end 4h after noon, with a total of 8±0.5 hours. When the solar collector facing south east, south west, east and west, and the testing time does not exceed the testing time when it is placed in the south, the testing duration should be no less than 4h [5].

However, most tests are just to meet the measured radiation requirements instead of strictly operated according to the heating performance test referred above. Certainly, it’s determined by the objective conditions.

3.4. Solar fraction ratio cannot reflect the system operating

By reverse calculation of the existing data from the testing 56 systems, we can get the average amount of hot water consumption is about 52L/person/day. The result is almost the same as the design load, but different from the actual using volume. Through the questionnaire surveys the actual using volume is about 34L/person/day. The reason is that in the field-testing of these systems, we used the design load to calculate the actual operating condition rather than using the actual demand.

Take a solar hot water system for example, assume it’s design hot water volume 150L, and design supplying temperature is 50 °C. The test results showed that under a certain irradiation weather the collecting heat from solar heat collector was 19.2MJ, the conventional energy consumption was 9.1MJ, solar fraction ratio was 68%, and the tested hot water consumption was 100L. By reverse calculation of the formula \[ Q = C \cdot m \cdot \Delta t \] we can find out that the temperature difference (\( \Delta t \)) is 45. But actually under the solar weather above, heating water to 50 °C the maximum temperature difference is only 35. This shows us that under the irradiation weather above, the solar condition could absolutely meet the heating need of 100 liter water to 50 °C. By the definition of solar fraction ratio, under this condition the solar fraction ratio should be 100%, but the test result is 68%. The test solar fraction ratio cannot really reflect the system operating conditions.

What’s the reason is that according to the current calculation, 32% of the energy was calculated for use to heat the part of water volume which is not the actual consumption, in this example, the part of water volume which is not the actual consumption is 150L-100L = 50L. This part of energy is useless for users. It is only used to meet the heating requirement of design volume. Because the design volume is too large, the consumption of this part of energy is accumulated all the time. It is estimated that a total of one-third of conventional energy is wasted.

In order to strengthen the comparison, we did a monitoring study. Through monitoring conventional electric water heater of a household over a period of one month, we identified the energy consumption required for heating water by electricity. The result showed that the energy consumption for monthly household heating hot water is 32kWh. The daily average energy consumption is only about 1kWh/d. Meanwhile the solar hot water system testing data showed a different result. In the solar hot water system above, the testing daily conventional energy consumption was 9.1MJ, equivalent to 2.5kWh, which was much larger than electric heating. The daily radiation of the solar hot water system above represents the good year. The detailed comparing results are shown in table 2.

<table>
<thead>
<tr>
<th>System</th>
<th>Data source</th>
<th>Environment condition</th>
<th>System parameters</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar hot water system</td>
<td>Field-testing</td>
<td>Solar radiation 16.79MJ/m², which represents the higher level of the entire year</td>
<td>Collecting heat from solar heat collector 19.2MJ, solar collector system efficiency 51%, solar fraction ratio 68%, electric heating assistant</td>
<td>Testing energy consumption 2.5kWh/d</td>
</tr>
<tr>
<td>Electric heater</td>
<td>Monitoring</td>
<td>Monitoring one month from 7/1/2014 to 7/31/2014</td>
<td>Shuaikang brand, volume 40L</td>
<td>Average energy consumption 1 kWh/d</td>
</tr>
</tbody>
</table>
3.5. Calculating result of the conventional energy substitution volume is too large

Currently, the calculating of conventional energy substitution volume \( Q_{bm} \) (tce) follows the formula as follows, according to the average equivalent coal consumption standard of 342 g/kWh by thermal power generation in 2012.

\[
Q_{bm} = \frac{x_1 Q_1 + x_2 Q_2 + x_3 Q_3 + x_4 Q_4}{3.6} \times 342/10^6
\]  

(6)

In which, \( Q_1, Q_2, Q_3, Q_4 \)--Daily collector heat gain (MJ/m\(^2\)•day), under specifically the four daily accumulated irradiance condition: \( J_1 < 8 \text{MJ/m}^2 \), \( 8 \text{MJ/m}^2 \leq J_2 < 13 \text{MJ/m}^2 \), \( 13 \text{MJ/m}^2 \leq J_3 < 18 \text{MJ/m}^2 \), \( J_4 \geq 18 \text{MJ/m}^2 \);

\( x_1, x_2, x_3, x_4 \)-- The number of the days above respectively over a year;

Take a solar hot water project’s testing and calculating results as example. The test results are shown in table 3.

<table>
<thead>
<tr>
<th>Test objects</th>
<th>Daily accumulated solar irradiance (MJ/m(^2))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>J&lt;8</td>
</tr>
<tr>
<td>Days (X1, X2, X3, X4)</td>
<td></td>
</tr>
<tr>
<td>Daily testing collector heat gain (Q1, Q2, Q3, Q4) MJ/m(^2)</td>
<td>7.9</td>
</tr>
<tr>
<td>Calculating collector heat gain over a year (Q1, Q2, Q3, Q4) MJ</td>
<td>3034.0</td>
</tr>
<tr>
<td>Conventional energy substitution volume all over the year (tce)</td>
<td>220.7</td>
</tr>
</tbody>
</table>

*Daily accumulated solar irradiance means the total solar radiation amount by the surface of heat collector. The testing time is counted untilled when meeting the accumulated solar radiation amount requirement. The daily accumulated solar irradiances in this test are respectively as follows: \( J_1 = 7.93 \text{MJ/m}^2 \), \( J_2 = 12.84 \text{MJ/m}^2 \), \( J_3 = 16.79 \text{MJ/m}^2 \), \( J_4 = 19.38 \text{MJ/m}^2 \)

As can be seen from table 3, the amount of conventional energy substitution value in this project is 220.7 tons coal equivalent one year. It is equivalent to 645,000 kWh in electricity savings. The project supplied hot water to a total of 384 households. So one household average amount of energy saving is about 0.575 tons coal equivalent per year, which is equivalent to 1680kWh in electricity savings annually.

In order to get the real annual hot water demand of one household, we use the following parameters into calculation: 3 persons in one household, hot water used only for shower, the shower using frequency in Summer (Jun.-Sep.) is 0.5 times / day per person, and in winter (Nov.- Feb.) is 0.143 times / day, in Spring and Autumn (the remaining 4 months) is 0.25 times / day, and the shower flowing rate generally is 6-8L / min (it is different because the building water supply and draining system has different pressure, in this case is 7L / min), and shower time in summer generally is 5-15min every time, in winter is 10-20min, in spring and autumn is 10-15min, average shower time is 16min every time. The calculation result for one household in one year is 36 tons, including hot water and cold water. The shower water temperature is assumed as 45 °C, with heated water temperature at 60 °C and cold water temperature at 15 °C, so the real annual hot water demand per household is 24 tons.

Based on the real annual hot water volume demand of one household, we can get the annual hot water heating energy consumption is 1256kWh, so one household’s total demand is 1256kWh one year. It is less than the electricity saving amount of solar hot water system (saving 1680kWh electricity annually). That’s unreasonable. Because according to the standard < Basic terminology of building energy-saving>, renewable energy substitution value definition: to achieve the same goal or purpose, comparing with a certain technology consuming conventional energy, the calculated energy saving by the new technology/system, the total demand should be larger than the amount of conventional energy substitution value, namely electricity savings in this case.

The calculating result for conventional energy substitution value is too large, which is even larger than the actual demand value. Take the calculating results mentioned above for example. If one household’s annual conventional energy substitution value is 1680kWh, comparing to actual usage of 1256kWh, there are 424kWh extra. It means we calculate 160 thousand kWh extra in a year.
4. Conclusions

Through the analysis in this paper, there are main problems as follows:

(1) Description of system in test report is not detailed which leading to invalid system samples.
(2) Because of objective circumstances, the test time point does not accord with the actual using condition.
(3) Test method and the reality do not match. Being lack of field test operability, the test procedure will greatly affect the accuracy of test results.
(4) The solar insuranceratio in solar hot water system cannot really reflect the system actual performance, which means the highersolar insuranceratio doesn’t represent less conventional energy consumption.
(5) The calculating result for conventional energy substitution volume is too large, out of normal range of values, even larger than the actual demand volume. This will affect the proposing and fulfilling of building energy efficiency goal to a certain extent in the future.

In short, through the analysis of test data of solar domestic hot water systems, we found that the system evaluation should be oriented by actual operating conventional energy consumption. There should be another method to calculate the conventional energy substitution volume more accurate. It could be compared with electric water heater. Thinking for evaluating solar hot water system should change from guarantee by solar to guarantee by conventional energy.

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