Comprehensive Benefits Evaluation of Solar Water Heating System Application in Energy Efficiency Retrofit of Existing Residential Buildings in Cold Climate Zone

Yiyang Liu¹*, Meijie Zhang¹ and Zebin Shen¹

¹School of Economics and Management, Beijing Jiaotong University, Beijing, 100044, China

*Corresponding author’s e-mail: 19120639@bjtu.edu.cn

Abstract. The application of renewable energy in energy efficiency retrofit of existing residential buildings is very important for energy conservation and emission reduction. Promoting the application of solar water heating system is conducive to the construction of comprehensive technical system for energy efficiency retrofit of existing residential buildings. Based on the case study, this research uses the comprehensive benefits evaluation methods to evaluate solar water heating system application in energy efficiency retrofit of existing residential buildings in cold climate zone, and concludes that the payback period and internal rate of return are 13.5 years and 4.11% respectively. It is suggested that electricity should be chosen as the auxiliary energy of solar water heating system and the government should increase subsidies and develop incentive mechanisms to encourage the application of solar water heating system.

1. Introduction

At present, building energy consumption of China accounts for more than 30% of the total energy consumption, and building energy conservation has become an important task of sustainable development strategy. Conducting energy efficiency retrofit of existing residential buildings is one of the important measures to reduce energy consumption in the construction field. Solar energy is clean, safe, easy to use and widely distributed, which makes it an ideal alternative energy. In order to build the comprehensive technology system of energy efficiency retrofit of existing residential buildings that executed 75% energy efficiency standards, it is very important to bring the application of solar water heating system into the scope of energy efficiency retrofit of existing residential buildings and evaluate its comprehensive benefits.

Existing literature focuses on the technical research and the economic benefits of solar water heating system in new buildings. Liu Yuqi analyzed the advantages and disadvantages and application scope of different types of solar water heating systems combined with engineering cases[1]. Ye Huiqian analyzed the economic benefits of various solar water heating systems in new civil buildings[2]. Muhammad obtained that the payback period of the solar water heating system is within 10 years[3]. Liu Yuming et al. carried out cost-benefit analysis on the application of solar water heating system in energy efficiency retrofit of existing buildings in Shenzhen, and obtained that the comprehensive benefits are good in areas with sufficient solar energy[4]. However, for the cold climate zone with low solar radiation in winter, there is a lack of research on the comprehensive benefits of practical application of solar water heating system. Based on the first comprehensive energy efficiency retrofit
project which executed 75% energy efficiency standards in China, this research evaluates the comprehensive benefits of solar water heating system application from economic and environmental benefits, explores the actual effect of solar water heating system application in cold climate zone, and provides policy suggestions for promoting the application of solar water heating system in energy efficiency retrofit of existing residential buildings.

2. Methods

2.1. Comprehensive benefit evaluation methods

2.1.1. Static investment payback period. The static investment payback period (Pt) refers to the number of years required to recover the investment by net benefit without considering the time value of capital. The calculation equation can be expressed as follows:

$$\sum_{t=0}^{P_t} (CI-CO)_t = 0$$  \hspace{1cm} (1)

In this equation, CI and CO represent cash input and cash output respectively; (CI-CO)_t is the net cash flow in the tth year. By comparing P_t and reference static investment payback period (P_c), the project’s economic sustainability can be evaluated. If P_t ≤ P_c, the evaluation results can be accepted. If P_t > P_c, it means the project should be rejected.

2.1.2. IRR. The IRR refers to the discount rate at which the accumulated NPV of the project is zero, and the formula is:

$$NPV(IRR) = \sum_{t=0}^{n} (CI-CO)_t (1+IRR)^{-t} = 0$$  \hspace{1cm} (2)

Here, n is the project’s lifetime. Then the IRR is compared with the hurdle cut-off rate(i_c) to assess the project’s financial viability. If IRR ≥ i_c, the evaluation results can be accepted. If IRR < i_c, the project is not economically acceptable.

2.2. Economic and environmental benefits calculation methods

2.2.1. Calculation methods of economic benefits. The annual energy savings of solar water heating system are its annual heat gain. Since solar energy is a free natural resource, it is necessary to convert solar energy into other conventional energy when calculating the economic benefits brought by solar water heating system application. The gross collector area A_c (m²) can be calculated by the following formula:

$$A_c = \frac{Q_w \rho W C_W (t_{end} - t_0) f}{J_t \eta_{cd} (1-\eta_L)}$$  \hspace{1cm} (3)

Where Q_w (L/d) represents the daily average water consumption; \( \rho W \) (kg/L) is the density of water; C_W (KJ/kg·℃) is specific heat capacity of water at constant pressure; t_end and t_0 represent final and initial temperature of water in the heat storage tank respectively; J_t (KJ/m²·d) is the annual average daily solar radiation on the daylighting surface of solar collectors at the local latitude angle; f is solar fraction; \( \eta_{cd} \) represents the annual average collector efficiency of solar collectors; \( \eta_L \) represents the heat loss rate of pipeline and water tank.

Then the annual heat gain of solar water heating system can be calculated by the following formula:

$$Q_{nj} = A_c J_t (1-\eta_L) \eta_{cd}$$  \hspace{1cm} (4)

In the formula, J_t represents the total annual radiation on the daylighting surface of solar collectors (MJ/m²·a).

The conventional energy substitution amount(Q_n) of solar water heating system can be calculated by the following formula:
Where $q$ represents the calorific value of standard coal, which is 29.307(MJ/kgce); $\eta_t$ represents the operating efficiency of the system with traditional energy as the heat source.

Assume that $P_r$ represents the market price of the conventional energy to be substituted, so the economic benefits of solar water heating system application can be calculated as follows:

$$B_{ECO} = Q_v \times P_r$$  \hspace{1cm} (6)

### 2.2.2. Calculation methods of environmental benefits.

Carbon dioxide($CO_2$), sulfur dioxide($SO_2$), nitrogen oxides($NO_x$) and other pollutants are produced during the combustion of standard coal. According to the discharge coefficient of pollutants, the formula for calculating pollutant emission reduction of solar water heating system can be expressed as below:

$$\Delta Q^p_j = Q_v \times \alpha_j$$  \hspace{1cm} (7)

Where $\Delta Q^p_j$ represents the emission reduction amounts of the $j$th type of pollutants; $\alpha_j$ is the discharge coefficient of the $j$th type of pollutants.

Assume that $P_j$ is the discharge price of the $j$th type of pollutants, then the environmental benefits of pollutants emission reduction by solar water heating system application can be calculated as follows:

$$B_H = \sum \Delta Q^p_j \times P_j$$  \hspace{1cm} (8)

### 2.2.3. Calculation methods of annual comprehensive benefits.

Since it is difficult to quantify the social benefits, only the economic and environmental benefits of the application of solar water heating system are considered in this research. Therefore, the annual comprehensive benefits of solar water heating system application are the sum of economic benefits and environmental benefits:

$$B_r = B_{ECO} + B_H$$  \hspace{1cm} (9)

### 3. Case analysis and Results

#### 3.1. Case description

The retrofit project in Huizhongli Residential Area, which is located in Beijing, is the first project which executed 75% energy efficiency standards in China. The retrofit scope includes the installation of solar water heating system of Building #309. The area of Building #309 is 5682 m². The original water heater is electric water heater, the operation efficiency of which is taken as 0.98. The initial investment of installation of solar water heating system is 974000yuan. The annual maintenance cost is 9740yuan. According to related design standard\[5\], the design parameters are shown in Table 1.

| Item                                      | Sign | Quantity |
|-------------------------------------------|------|----------|
| Daily average water consumption(L)        | $Q_W$| 10800    |
| The density of water(kg/L)                | $\rho_W$| 1       |
| Specific heat capacity of water at constant pressure(KJ/kg·℃) | $C_W$| 4.187    |
| The initial temperature of water in the heat storage tank(℃) | $t_0$| 11.5     |
| The final temperature of water in the heat storage tank(℃) | $t_{end}$| 60      |
| Annual average daily solar radiation on the daylighting surface of solar collectors at the local latitude angle(KJ/m²·d) | $J_t$| 15261.14 |
| Annual average collector efficiency of solar collectors | $\eta_{col}$| 0.46     |
| Heat loss rate of pipeline and water storage tank | $\eta_L$| 0.20     |
| Solar fraction                           | $f$ | 0.50     |
| Total annual radiation on the daylighting surface of solar collectors (MJ/m²·a) | $J_f$| 6582.78  |

In order to vigorously promote the application of solar water heating system, Beijing Municipality...
gives subsidies according to the collector area of solar water heating system, which is 200 yuan per square meter.

3.2. Results

3.2.1. Economic benefits of solar water heating system application.
According to equation (3) and (4), the gross collector area and annual heat gain of solar water heating system can be calculated, the results of which are 195.26 m² and 473,010.13MJ respectively. There is an energy unit conversion relationship that 1 kWh =3.6MJ. Applying equation (5), it can be calculated that the annual electricity savings of solar water heating system are 134,073.2 kWh. According to related market information in China, the price of electricity in Beijing is 0.5383 yuan/kWh. Applying equation (6), the economic benefits of solar water heating system application are 72171.6 yuan.

3.2.2. Environmental benefits of solar water heating system application.
According to equation (5), annual coal consumption savings of solar water heating system application are 16.47tce. Pollutant discharge coefficients of standard coal combustion and discharge fees in Beijing are shown in Table 2.

| Pollutants | Discharge coefficient (t/tce) | Discharge fees (yuan/t) |
|------------|------------------------------|------------------------|
| CO₂        | 0.67                         | 160                    |
| SO₂        | 0.0165                       | 10000                  |
| NO₅        | 0.0156                       | 10000                  |

According to Table 2 and equation (7), annual emission amounts of CO₂, SO₂ and NO₅ can be calculated, and the results are 11.03t, 0.27t and 0.26t respectively. Applying equation (8), it can be calculated that the environmental benefits of solar water heating system application are 7064.8yuan.

3.2.3. Comprehensive benefits evaluation. According to equation (9), the comprehensive benefits brought by the application of solar water heating system is 79236.4 yuan. The subsidy for the project is 39052 yuan. Assume that the lifetime of the solar water heating system is 20 years, so applying equation (1) and (2), Pt and IRR of solar water heating system application in this project can be calculated, the results of which are 13.5 years and 4.11% respectively. The electricity saving amount per m² is 23.6kWh. The application of solar water heating system can recover the cost in the life cycle, but it is less attractive to market investors.

4. Discussion

4.1. Auxiliary energy selection
The energy-saving effect and cost-effectiveness of solar water heating system are affected by auxiliary energy selected[6]. Assume that the original water heater is natural gas water heater, and its operation efficiency is 0.84. The market price of natural gas is 2.63 yuan/m³. The evaluation index comparison of solar water heating system with different auxiliary energy is shown in Table 3.

| Auxiliary energy | coal consumption savings(tce) | CO₂ emission reduction(t) | SO₂ emission reduction(t) | NO₅ emission reduction(t) | Pt(year) | IRR(%) |
|------------------|-------------------------------|---------------------------|---------------------------|---------------------------|----------|--------|
| Electricity      | 16.47                         | 11.03                     | 0.27                      | 0.26                      | 13.5     | 4.11   |
| Natural gas      | 19.21                         | 12.87                     | 0.32                      | 0.30                      | 25.6     | -2.25  |

It can be seen from Table 3 that although the environmental benefits of solar water heating system are better when the auxiliary energy is natural gas, the comprehensive benefits are not as good as that of solar water heating system when electricity is used as auxiliary energy due to poor economic
benefits. When the solar water heating system is applied in energy efficiency retrofit of existing residential buildings, it is suggested to select the electric water heater as the auxiliary energy.

4.2. The impact of subsidy
The initial investment of solar water heating system is large. The subsidy given by the government is equivalent to increasing the income of the project, which has a positive impact on the economic benefits of the project. If the government subsidies are canceled, it can be seen from the calculation results that \( P_t \) is 14.0 years and IRR is 3.66%. The results show that the current subsidies have little effect on promoting the application of solar water heating system. It is necessary to increase subsidies or develop incentive mechanisms to promote the application of solar water heating system in the energy efficiency retrofit of existing residential buildings.

4.3. Problems in practical application of solar water heating system in cold climate zone
After installing the solar water heating system in Building #309, it was actually suspended after only three years of use. The reason is that there are two main problems in the practical application of solar water heating system: (1) In the process of retrofit, the water inlet pipe will occupy the indoor space of some residents' living room, which is not beautiful, and there may be a shortage of hot water during the peak period of hot water use, so the residents' experience is not good. Then they give up using it. (2) In the severe cold period of winter, the exposed pipes of solar water heating system are easy to suffer from frost cracking and damage and cannot be used. Maintenance is not timely when there is no certain scale of use. The above two problems should be solved.

5. Conclusions
The application of solar water heating system in energy efficiency retrofit of existing buildings can bring better energy-saving effect and cost-effectiveness, so it is important to insist on mandatory installation of solar water heating system in retrofit. When installing solar water heating system, it is more economical to choose electricity as auxiliary energy. However, now the comprehensive benefits brought by solar water heating system application are still not attractive to market investors. So the government should increase subsidies or develop incentive mechanisms to encourage enterprises to invest solar water heating system. There are some problems in the practical application of solar water heating system in cold climate zone. It is necessary to solve these problems to promote the further application of solar water heating system in energy efficiency retrofit of existing residential buildings.

Acknowledgments
This research is supported by the Social Science Foundation of Beijing Municipal Commission of Housing and Urban-Rural Development (Project number: B20SK00100).

References
[1] Liu, Y.Q. (2019) Analyze the design and application of different forms of solar hot water system in residential buildings. Shanxi Architecture, 45: 173-174.
[2] Ye, H.Q. (2008) Economic analysis of solar hot water system for newly built civil buildings. Zhejiang Construction, 11: 70-71.
[3] Muhammad, S. (2018) Solar water heating system for residential consumers of Islamabad, Pakistan: A cost benefit analysis. Journal of Cleaner Production, 172: 2443-2453.
[4] Liu, Y.M., Guo, X., Hu, F.L. (2014) Cost-benefit analysis on green building energy efficiency technology application: A case in China. Energy and Buildings, 82: 37-46.
[5] MOHURD. (2013) Evaluation standard for application of renewable energy in buildings. China Architecture & Building Press, Beijing.
[6] Yu, G.Q., Wu, J.L., Zuo, P. (2015) Influence of auxiliary heating on energy saving of solar water heating system. Water & Wastewater Engineering, 41: 75-78.