Post-evaluation of a ground source heat pump system for residential space heating in Shanghai China

Y Lei¹,², H W Tan¹,²,³,⁵ and L Z Wang⁴
¹School of Mechanical and Energy Engineering, Tongji University, Shanghai 201804, China
²Research Center of Green Building and New Energy, Tongji University, Shanghai, 200092, China
³UNEP-Tongji Institute of Environment for Sustainable Development 200092, China
⁴Shanghai Research Institute of Building Sciences, Shanghai 201108, China
E-mail: hw_tan@tongji.edu.cn

Abstract. Residents of Southern China are increasingly concerned about the space heating in winter. The chief aim of the present work is to find a cost-effective way for residential space heating in Shanghai, one of the biggest city in south China. Economic and energy efficiency of three residential space heating ways, including ground source heat pump (GSHP), air source heat pump (ASHP) and wall-hung gas boiler (WHGB), are assessed based on Long-term measured data. The results show that the heat consumption of the building is 120 kWh/m²/y during the heating season, and the seasonal energy efficiency ratio (SEER) of the GSHP, ASHP and WHGB systems are 3.27, 2.30, 0.88 respectively. Compared to ASHP and WHGB, energy savings of GSHP during the heating season are 6.2 kgce/(m²·y) and 2.2 kgce/(m²·y), and the payback period of GSHP are 13.3 and 7.6 years respectively. The sensitivity analysis of various factors that affect the payback period is carried out, and the results suggest that SEER is the most critical factor affecting the feasibility of ground source heat pump application, followed by building load factor and energy price factor. These findings of the research have led the author to the conclusion that ground source heat pump for residential space heating in Shanghai is a good alternative, which can achieve significant energy saving benefits, and a good system design and operation management are key factors that can shorten the payback period.

1. Introduction
After a period of heavy snow and freezing weather in Southern China at the beginning of 2013, the debate over whether the government should provide central heating in the south of China is becoming more intense. Up to now, the central heating systems cover about 70% of the urban building area in Northern China (Yellow River basin and its north) but less than 5% of the urban building area in Southern China (Yangtze River basin, Hunan, Guizhou, and Yunnan etc.) [1]. During the winter season, the indoor as functions of residential buildings without central heating systems are fluctuated as functions of the change of outdoor temperature in China's hot summer and cold winter region. And the average indoor temperature is only 10-17°C, which is far from ASHRAE comfort zone [2,3]. Therefore, space heating in winter is becoming an urgent need for residents in those areas.

For the purpose of finding a cost-effective way of residential space heating in China's hot summer
and cold winter region, energy efficiency and economic feasibility of three residential space heating ways, including ground source heat pump (GSHP), air source heat pump (ASHP) and wall-hung gas boiler (WHGB), are assessed based on Long-term measured data in the present study.

2. Systems description

2.1. Building
The testing building is located in Shanghai (31.20°N, 121.21°E). It is a three-storey private residential house, with a total gross floor area of 280 m² and air-conditioned area of 180 m². Figure 1 shows the second-floor plan of the building. The average low temperatures in the area in January are about 4.3°C. There are approximately 1648 heating degree days (18°C base). The peak value of the heat consumption was calculated as 20 kW, equivalent to 110 W/m². The occupancy time of the building is from 17:00 to 08:00 next day for the working days and 24 h for weekend.

![Figure 1. The second-floor plan of the building.](image)

2.2. Space heating systems

2.2.1. GSHP heating system. The GSHP heating system installed in the testing building is mainly composed of three parts of ground heat exchanger (GHE), mechanical equipment (including heat pump and circulating pumps), and radiant floor heating terminal units. The detailed specifications and main technical parameters of the GSHP heating system were given in table 1.

| Table 1. The parameters of the main components in GSHP heating system. |
|---------------------------------------------------------------|
| **Ground heat exchanger (GHE)**                               |
| Type of GHE         | Vertical single U-bend                                      |
| Material of U-bends | HDPE high density polyethylene                             |
| Size of U-bends     | Φ32 mm×3.2 mm                                               |
| Depth of boreholes  | 5×90 m                                                      |
| **Mechanical equipment**                                     |
| Heat pump           | Rated heating capacity 16 kW /inverter                     |
|                     | / DAKIN EEHS-6P                                             |
2.2.2. Reference systems. Two conventional heating systems, which are the most commonly used for space heating in Shanghai, were selected as reference system in this study. One is a wall-hung gas boiler (WHGB) with a heating capacity of 20 kW, and the other is a heating system composed by eight split air source heat pumps (ASHP). The heating capacity of a single ASHP unit is about 3.5 kW.

2.3. Data acquisition system
A network data-acquisition system was designed to monitor the key operating parameters of GSHP system and ASHP system. The following data were regularly recorded every 5 minutes for GSHP system and ASHP system, respectively.

The parameters monitored for GSHP system as follows:
- Electrical power input to the compressor and circulating pumps by using watt-hour meters;
- Supply /return water temperature and water flow rates of the GHE by using an ultrasonic calorimeter with resistance thermometers (Pt100).
- Supply /return water temperature and water flow rates of the radiant floor heating system by using an ultrasonic calorimeter with resistance thermometers (Pt100).
- Ambient and indoor air temperatures by using resistance thermometers (Pt100).

The parameters monitored for ASHP system as follows:
- Electrical power input to the compressor and fans by using a watt-hour meter;
- Supply /return air temperatures of outdoor and indoor unit by using resistance thermometers (Pt100);
- Circulating air flow rates of outdoor and indoor unit by using hot-wire anemometers.

3. Analysis methods

3.1. Energy consumption and efficiency

3.1.1. Heat consumption. A calorimeter was used to monitor the thermal energy supplied to the building. Therefore, the heat consumption of the building in the Δτ interval starting at τ₀ time was integrated by the following formulas.

\[ Q = \int_{\tau_0}^{\tau_0+\Delta \tau} Q(\tau)\,d\tau \]  
\[ Q(\tau) = m_{w,\tau} c_{p,w} (t_{sW,\tau} - t_{rW,\tau}) \]  

Where \( Q(\tau) \) is the instantaneous heat consumption, \( m_{w,\tau} \) is the instantaneous mass flow rate of water, \( c_{p,w} \) is the specific heat capacity of water, \( t_{sW,\tau} \) and \( t_{rW,\tau} \) represent the instantaneous temperature of supply water and return water, respectively. And the heat consumption per unit area over the heating season was calculated by using equation (3).

\[ q_s = \frac{Q_{\tau_{end}}^{\tau_{start}}}{A} \]  

Where \( A \) is the total space heating area, \( Q_{\tau_{end}}^{\tau_{start}} \) is the total heat consumption over the heating season, \( \tau_{start} \) and \( \tau_{end} \) represent the space heating start and stop times, respectively.

3.1.2. GSHP system performance calculation. The energy consumption of the GSHP heating system consists of the electricity consumption of the heat pump units and water circulating pumps. The electricity consumption is monitored by electricity meters through integrating instantaneous power consumption \( (N(\tau)) \) by using equation (4).
The coefficient of performance (COP) of the GSHP unit (COP_{GSHP, unit}) and the whole GSHP heating system (COP_{GSHP, sys}) were calculated by equations (5) and (6), respectively.

\[
COP_{GSHP, unit} = \frac{Q}{N_{GSHP}} \tag{5}
\]

\[
COP_{GSHP, sys} = \frac{Q}{N_{GSHP} + N_{pump}} \tag{6}
\]

Where \( N_{GSHP} \) is the electricity consumption of GSHP unit, and \( N_{pump} \) is the electricity consumption of water circulating pumps including circulating pumps of ground coupling loop and circulating pump of radiant floor heating loop.

The seasonal primary energy ratio of GSHP heating system (SPER_{GSHP,sys}) was calculated by

\[
SPER_{GSHP,sys} = \varepsilon \cdot SEER_{GSHP,sys} \tag{7}
\]

Where \( \varepsilon \) is the power generation efficiency, according to statistics [4], the power generation efficiency in the present study is set to 0.31. \( SEER_{GSHP,sys} \) is the seasonal energy efficiency ratio of GSHP heating system, which was calculated by equation (8)

\[
SEER_{GSHP,sys} = COP_{GSHP,sys} \frac{t_{end}}{t_{start}} \tag{8}
\]

3.1.3. Reference system calculation. A split air source heat pump (ASHP) heating system was investigated experimentally. The following parameters were monitored for a long period with 5-minute intervals, including the power consumption of the system (\( N_{ASHP} \)), supply air temperature (\( t_{sa,\tau} \)), return air temperature (\( t_{r,a,\tau} \)), circulating air flow (\( m_{a,\tau} \)), ambient temperature (\( t_{a,\tau} \)), etc. The instantaneous COP of the ASHP heating system was calculated using the following formula:

\[
COP_{ASHP,sys}(t_{a,\tau}) = m_{a,\tau}c_{p,a}(t_{sa,\tau} - t_{r,a,\tau})/N_{ASHP} \tag{9}
\]

Considering the impact of ambient temperature on the COP of the ASHP heating system, the seasonal energy efficiency ratio of ASHP heating system (SEER_{ASHP,sys}) was estimated as weighted average of \( COP_{ASHP,sys} \) on different ambient temperature conditions, using the following formula:

\[
SEER_{ASHP,sys} = \sum \omega(t_{a,\tau}) \cdot COP_{ASHP,sys}(t_{a,\tau}) \tag{10}
\]

Where \( \omega(t_{a,\tau}) \) is the probability of ambient temperatures which are between \( t_{a,\tau} \) and \( (t_{a,\tau} + 0.5) \)°C during the whole heating season. The seasonal primary energy ratio of ASHP heating system (SPER_{ASHP,sys}) was calculated by

\[
SPER_{ASHP,sys} = \varepsilon \cdot SEER_{ASHP,sys} \tag{11}
\]

The energy efficiency ratio of wall-hung gas boiler (WHGB) heating system is equal to the primary energy ratio of WHGB heating system at about 0.85-0.90 [6], and it does not vary with changes of the ambient temperature. The seasonal energy efficiency ratio and the seasonal primary energy ratio of WHGB heating system (SEER_{WHGB,sys} and SPER_{WHGB,sys}) were set to 0.88.

We assumed that both the building heat consumption over the heating season by using reference heating systems (ASHP or WHGB) and GSHP heating system are the same. So, the energy consumption (EC) and primary energy consumption (PEC) of three heating systems were calculated by equations (12) and (13) respectively.

\[
EC = Q|_{t_{start}}^{t_{end}} / SEER \tag{12}
\]

\[
PEC = Q|_{t_{start}}^{t_{end}} / (29.3 \cdot SPER) \tag{13}
\]
Where value of 29.3 is the calorific value of coal equivalent.

3.2. Economic analysis

To determine whether GSHP would produce any economic benefits for home owners, an economic analysis was carried out to compare GSHP with ASHP and WHGB system.

3.2.1. Initial cost. According to actual situation of the project construction and estimated using data from local contractors, equipment suppliers and construction estimating software, the investment cost, including material, labor, and taxes, for the three heating systems compared are given in Table 2 [6].

| Systems | Item                  | Cost (Yuan) |
|---------|-----------------------|-------------|
| GSHP    | Ground heat exchanger system | 19,000      |
|         | Equipment             | 25,000      |
|         | radiant floor heating system | 28,000    |
|         | **Total**             | **72,000**  |
| ASHP    | Equipment             | 38,000      |
|         | installation and debugging | 14,000    |
|         | **Total**             | **52,000**  |
| WHGB    | Equipment             | 20,000      |
|         | radiant floor heating system | 28,000    |
|         | **Total**             | **48,000**  |

3.2.2. Annual operating cost. The annual operating costs of a space heating system include the costs of fuel and maintenance of equipment. The annual operating costs (AC) were given as:

\[ AC = EC \cdot FP + MC \]  

Where FP is fuel price, MC is equipment maintenance costs. Values of FP and MC are given in Table 3 and 4, respectively.

| Fuel type         | Unit cost     |
|-------------------|---------------|
| Electricity       | 0.67 Yuan/kWh |
| Natural gas       | 2.9 Yuan/m³   |

3.2.4. Economic comparison. To study the economic feasibility of a system, different methods could be used to evaluate the different figures of merit of the systems. Some examples are: Net present value method, the internal rate of return method, the annual cost and other methods [8]. In this study, the present worth (PW) method has been used to compare the cost effectiveness of the three heating systems.

The PW method refers to all the events in an economy, both incomes and expenditures, as one figure at one point in time. When comparing different alternatives for a given revenue or cost saving, the alternative with the least present worth of all expenditures or annual charges is to be preferred.
Therefore, comparing the present worth of alternative A with alternative B, the payback period (PP) of alternative A would be the point-in-time when the present worth of B over that of A. The present worth (PW) was given as:

$$PW = IC + AC \cdot \frac{1}{i} \left[1 - (1 + i)^{-n}\right]$$

Where $IC$ is the initial cost, $AC$ is the annual operating cost, $i$ is interest rate, and $n$ is number of interest periods.

3.2.5. Sensitivity analysis. The PW method can be used for assessing the economic feasibility of different heating systems, but the result is subject to many uncertainties. Such as the building heat consumption, the system energy efficiency is uncertain due to the impact of the human behavior and test instruments accuracy, and fuel price also has some uncertainty. Thus, analysis of these uncertainties impact on the economy of the heating system is also very important.

Sensitivity analysis is very useful when attempting to determine the impact the actual outcome of a particular variable will have if it differs from what was previously assumed. By creating a given set of scenarios, the analyst can determine how changes in selected variables will impact the target variable. In this respect, the sensitivity analysis of the key factors that affect the payback period is carried out. For sensitivity analysis, three key parameters, including building heat consumption ($q_o$), the seasonal energy efficiency ratio of GSHP heating system ($SEER_{GSHPSys}$) and fuel price (FP), were to be increased and decreased by 20% of their original value.

4. Results and discussions

4.1. Variation of ambient temperature and heat consumption

The ambient temperature is a key factor for building heat consumption and performance of heating systems. In order to observe and find out the interaction of energy consumption and coefficients of heating systems performance with ambient temperatures, the ambient temperature was measured continuously during the heating season. The measured data show that the ambient temperature was changing in the range of -2 to 20°C. Figure 2 represents the distribution of probability of ambient temperatures over the heating season. As we can see from the figure, the outdoor temperature is mainly distributed in the range of 2 to 13°C, accounting for a proportion more than 90%. And the weighted average value of the ambient temperature during the whole heating season is 7.96°C.
Figure 2. Probability density of ambient temperature during heating season.

Figure 3. Variation of heat consumption with ambient and indoor temperature.
Figure 4. Variation of heat consumption in a typical day.

The variations of heat consumption, ambient temperature and indoor temperature during the heating season are shown in Figure 3. And Figure 4 shows the hourly variation of heat consumption in a typical day. As these two figures suggested that the indoor temperature is mainly maintained at 19-23 \( ^\circ \)C, and the heat consumption and outdoor temperature has a very significant correlation. Figure 5 indicates that the average value of heat load is a linear function of ambient temperature. During the heating season, the maximum heat load is about 80 W/m\(^2\) when the ambient temperature reached 0 \( ^\circ \)C, and the heat consumption per unit area over the heating season calculated by equation (3) is 120 kWh/m\(^2\).

Figure 5. Average heat consumption versus ambient temperature.

4.2. Performance of GSHP heating system
The energy performance of a GSHP heating system can be influenced by three primary factors: (a) the
heat pump machine, (b) the circulating pump and (c) the ground coupling. The heat pump is the largest single energy consumer in the system. Its performance is a function of the efficiency of the machine and the water temperature produced by the ground coupling [7].

Figure 6. Unit and system COP values of GSHP during a heating period.

Based on the measured data, the COP of the heat pump unit \((COP_{GSHP,unit})\) and the whole system \((COP_{GSHP,sys})\) during the heating season were calculated by using equations (5) and (6). Figure 6 shows the hourly average values of \(COP_{GSHP,unit}\) and \(COP_{GSHP,sys}\) during a long-term heating period, from Dec. 2012 to Feb. 2013. It is clear from this figure that the values of \(COP_{GSHP,unit}\) and \(COP_{GSHP,sys}\) are relatively stable except some outlier points. The highest COP values were observed as 4.65 for the heat pump and 4.16 for the system at the beginning of the heating season, when the water temperature produced by the ground coupling reached a relatively high value at 17.2°C. About one month later since the starting time of heating, the water temperature produced by the ground coupling stabilized at 12°C to 13.5°C and the \(COP_{GSHP,unit}\) and \(COP_{GSHP,sys}\) varied between 3.51-4.25 and 3.2-3.6 respectively. The value of the seasonal energy efficiency ratio of GSHP heating system \((SEER_{GSHP,sys})\) and the seasonal primary energy ratio of GSHP heating system \((SPER_{GSHP,sys})\) which calculated by equations (8) and (7), is 3.27 and 1.01, respectively.

4.3. Performance of ASHP heating system
To determine the actual heating performance of an air source heat pump, a split ASHP was investigated experimentally under different weather conditions. The COP of the ASHP heating system was calculated using the equation (9), and Figure 7 shows the average values of \(COP_{ASHP,sys}\) under different ambient temperatures at 0.5°C interval. As the figure shows, the \(COP_{ASHP,sys}\) with ambient temperature is a linear relationship. The \(COP_{ASHP,sys}\) reached 3.57 when the ambient temperature get 12.5°C, but only 1.50 when the outdoor temperature dropped to 2°C.

According to this function between \(COP_{ASHP,sys}\) and ambient temperature, and the above-mentioned distribution probability of ambient temperatures over the heating season, the seasonal energy efficiency ratio of ASHP heating system \((SEER_{ASHP,sys})\) and the seasonal primary energy ratio of ASHP heating system \((SPER_{ASHP,sys})\) calculated by equations (10) and (11) are 2.30 and 0.71, respectively.
4.4. Energy efficiency comparison

Table 5. Energy efficiency comparison.

| Item                        | GSHP   | ASHP   | WHGB  |
|-----------------------------|--------|--------|-------|
| $q_s$ (kWh/m$^2$)           | 120    | 120    | 120   |
| SEER                        | 3.27   | 2.30   | 0.88  |
| SPER                        | 1.01   | 0.71   | 0.88  |
| EC (kWh(e)/m$^2$, Nm$^3$(g)/m$^2$) | 36.7(e) | 52.2(e) | 15.8(g) |
| PEC (kgce/m$^2$)            | 14.5   | 20.7   | 16.7  |

Based on the above-calculated results, the comparison of energy efficiency of three heating systems is given in table 5. As the table shows, the GSHP heating system has the highest seasonal primary energy ratio (SPER), followed by WHGB. Compared with ASHP and WHGB, the annual energy saved per unit heating area by GSHP is 6.2 kgce and 2.2 kgce, respectively. This has confirmed that GSHP is the most energy efficient way for space heating in Shanghai.

4.5. Economic feasibility evaluation

The present worth (PW) of three heating systems has been calculated by using equation (16) with a lifetime of 25 years and an interest rate of 5.6%. Figure 8 illustrates the variation of the present worth (PW) of three systems versus the operation life. As can be seen from the figure, at the twenty-five years, PW value of the GSHP system is the minimum and that of WHGB is the maximum. This result proves that the GSHP heating system is to be preferred among three heating systems. Compared with ASHP and WHGB heating system, the payback periods of GSHP system are 13.3 and 7.6 years.
Figure 8. Variation of the present worth versus the operation life of the system.

Figure 9. Sensitivity analysis of the payback period of GSHP compared with WHGB and ASHP.

To determine which parameters are the key drivers of the payback period of GSHP system, a sensitivity analysis is carried out. Three key parameters, including building heat consumption \( (q_s) \), the seasonal energy efficiency ratio of GSHP heating system \( (SEER_{GSHP,sys}) \) and fuel price \( (FP) \), were to be increased and decreased by 20% of their original value. The calculated results are shown in Figure 9. It is clear from this figure that the payback period of GSHP compared with WHGB and ASHP decreased with one of the parameters \( (q_s, SEER_{GSHP,sys} \) and \( FP \)) increased. Among these three key parameters, the \( SEER_{GSHP,sys} \) is the most important parameter affecting the payback period of GSHP both compared with WHGB and ASHP.

5. Conclusions

Energy efficiency and economic feasibility analysis of three heating systems for residential building in Shanghai was carried out in the present study. From the results of the experimental study, the following conclusions may be drawn:

- The average ambient temperature during the whole heating season is 7.96 °C. The peak heat load of the residential building is about 80 W/m², and the total heat consumption is 120
The values of seasonal energy efficiency ratio (SEER) of the GSHP, ASHP and WHGB heating systems are 3.27, 2.30 and 0.88, respectively. And the corresponding values of seasonal primary energy ratio are 1.01, 0.71 and 0.88, respectively. Compared to ASHP and WHGB, energy savings of GSHP during the heating season are 6.2 kgce/(m².y) and 2.2 kgce/(m².y). Those results indicate that the GSHP heating system is the most efficient way for residential space heating in Shanghai.

Comparing with ASHP and WHGB, the present worth (PW) value with 25 years lifetime of GSHP is the minimum, and the payback periods are 13.3 and 7.6 years, respectively. This proves that the GSHP heating system is to be preferred among three heating systems.

The sensitivity analysis results suggested that the seasonal energy efficiency ratio of GSHP heating system is the most important parameter affecting the payback period of GSHP heating system. Therefore, a good system design and operation management are the key factors that can shorten the payback period.

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Appendix A

| Nomenclature       | Description                                           |
|---------------------|-------------------------------------------------------|
| A                   | The total heating space area [m²]                     |
| AC                  | The annual operating costs [Yuan]                    |
| ASHP                | Air source heat pump                                  |
| COP                 | The coefficient of performance[kWh/kWh]              |
| EC                  | Energy consumption [kWh]                             |
| FP                  | Fuel price [Yuan/kWh, Yuan/Nm³]                       |
| GSHP                | Ground source heat pump                               |
| IC                  | The initial cost [Yuan]                               |
| m                   | Mass flow rate [kg/h]                                |
| MC                  | Maintenance costs [Yuan]                             |
| n                   | Number of interest periods [year]                     |
| N                   | Electricity consumption [kWh]                         |
| ε                   | The power generation efficiency [%]                   |
| PEC                 | Primary energy consumption [kgce]                    |
| PP                  | The payback period [year]                            |
| PW                  | The present worth [Yuan]                             |
| Q                   | Heat consumption [kWh]                               |
| q                   | Heat consumption per unit area [kWh/m²]              |
| SEER                | Seasonal energy efficiency ratio [kWh/kWh]           |
| SPER                | Seasonal primary energy ratio [kWh/kWh]              |
| t                   | Temperature [°C]                                     |
| τ                   | instantaneous time [h]                              |
| Δτ                  | time interval [h]                                    |
| i                   | interest rate [%]                                    |
| a                   | ambient                                              |
| pump                | pump                                                 |
| ra                  | return air                                           |
| rw                  | return water                                         |
| unit                | unit                                                 |
| s                   | the heating season                                    |
| sa                  | supply air                                           |
| sw                  | supply water                                         |
| sys                 | system                                               |
| w                   | water                                                |

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