Economic analysis of the solar thermal and air source heat pump combined system for energy demand of buildings in China

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Abstract. This study focuses on the economy of the solar thermal and air source heat pump combined system supplying the same demand of SH and DHW for a city household at different locations in China, namely; Beijing, Xi’an and Nanjing. These three locations represent the climatic conditions variety in China with different outdoor temperatures and solar radiation. At each location, the optimized simulations are carried out to recognize the most economical configurations. The results show that, for a 15-year running time, the system comprising 10m² solar collectors and 5 kW air source heat pump is the best configuration having the minimum cost for all three cities, but the minimum cost of which is different for each location. At Nanjing, the system has the lowest cost of all the three cities, and the payback time of which is also the shortest. However, the payback time of the optimum system in Beijing is 15.9 years exceeding its running time, due to the lowest central heating fee included in the cost of the traditional heating method.

1. Introduction
Recently, utilization multi renewable energy sources synthetically based on the system integration, which is stable, reliable and efficient, is a direction of energy science and has a great prospect. And just so, the solar thermal and air source heat pump combined system for SH and DHW in buildings is increasingly being designed and studied [1-6]. The climate conditions can affect the performance and economy of the solar thermal and air source heat pump combined system. At present, there is little relevant literature that simultaneously discuss the effect of climate on the economy of the system, with a specific focus on Chinese mainland. Therefore, the aim of this study was to fill this gap by comparing the cost and payback time of the solar thermal and air source heat pump combined system for a vast range of China with different climatic conditions, which is of great significance to China energy conservation, cost saving and environmental protection. China has a vast geographical environment, so climate conditions vary widely. According to accumulative temperature, it is divided into five temperature regions[7]. In this paper, three representative cities with different climatic conditions have been considered, which are Beijing (warm temperate zone; very rich irradiation), Xi’an (warm temperate zone; rich irradiation), and Nanjing (subtropical zone; rich irradiation). So, in the present study, economy analysis of using the system to meet the same demand of SH and DHW for a city family house in these three regions of China is carried out. Firstly, different sizes of the main components (solar collectors or air source heat pump) lead to different configurations of the system. Each configuration should meet the energy demand and the one that has the minimum cost is taken as the optimum configuration. Secondly, the optimal simulation results of the system are explained in
detail for a city family house in Beijing. And the simulations are repeated for the other two different locations namely; Nanjing and Xi’an. Thirdly, the optimal simulation results in three regions are summarized, in order to compare the system at different locations in terms of the economy. Finally, the payback period of the optimal system with respect to local traditional heating method is calculated to determine economic feasibility.

2. Mathematical model in Polysun

The optimization of the solar thermal and air source heat pump combined systems are achieved by Polysun software. In the simulation, the area of solar collectors or the capacity of the heat pump is increased until there is no shortage of the power supply to the energy demand of DHW and SH. Difference in area of solar collectors or capacity of the air source heat pump lead to various system configurations. In Polysun, the best optimal configuration is the lowest total cost as well as meeting the energy demand of SH and DHW.

The total cost of a system (CS) is defined as:

$$CS = ICS + RCS$$  \(1\)

Where $ICS$ is investment cost of all system components. $RCS$ is the running cost of the system in project life time.

$$ICS = C_{solar collector} + C_{air heat pump} + C_{tank} + C_{other components}$$  \(2\)

Where $C_{solar collector}$, $C_{air heat pump}$, $C_{tank}$, and $C_{other components}$ are the sum of present value of the solar collectors, air pump, water tank, and other needed components(such as water pumps and pipes), respectively, during the system lifetime. Considering a mid-sized single-family house has less initial investment, $ICS$ is to invest funds at one time, without definition the annuity payment.

$$RCS = E_{elec} \times N + MCS$$  \(3\)

Where $E_{elec}$ is the annual total electricity consumption of the system. $N$ is the project lifetime in years. $MCS$ is the maintenance cost of system, which is calculated as 1% of their $ICS$. The present local market price used for the $CS$ are all listed in Table. 1.

The contribution of the solar energy or air energy to the system can be respectively evaluated by the solar fraction($SF$) and air fraction($AF$). $SF$ is percentage of energy to the system supplied by the sun, which is expressed as:

$$SF = \frac{Q_{solar}}{Q_{use}}$$  \(4\)

Where $Q_{solar}$ is annual air energy to the system. $Q_{use}$ is annual total energy consumed for DHW and SH. $AF$ is percentage of energy to the system supplied by the air source, which is expressed as:

$$AF = \frac{Q_{air}}{Q_{use}}$$  \(5\)

Where $Q_{air}$ is annual air energy to the system.

| Item                        | Value  | Unit    |
|-----------------------------|--------|---------|
| Flat-plate collector        | 600    | CNY/m²  |
| Water tank (500L)           | 2800   | CNY     |
| Other needed components     | 1200   | CNY     |
| Electricity price           | 0.5    | CNY/kWh |
| Air source heat pump(5kW)   | 15,000 | CNY     |
| Air source heat pump(10kW)  | 25,000 | CNY     |

3. results and analysis

3.1. Simulation results
Solar(air) energy resource is used through solar collectors(air source heat pump) to supply energy for DHW and SH demand of a mid-sized single-family house located in city of Beijing (east longitude: 116.4°E, northern latitude: 39.93°N), China. The DHW need is 200 L/d of water at 45°C. The heated area of the building is 150 m². The indoor heating set temperature is 19°C during the day and night in the heating period from Nov 1st until Mar 1st next year. The project lifetime of each system is 15 years. Fig. 1 shows a schematic diagram of this system. The area of solar collectors varies from 10 m² to 34 m², and the power of the air heat pump varies from 5 kW to 35 kW. Among these configurations, the one that has the minimum cost of the system (CS) in project lifetime is to be considered. Fig. 2 and Fig. 3 respectively shows the energy balance and the CS variation under different areas of solar collectors, when the capacity of the heat pump is 5 kw. It is clear that, with the increasing of solar collectors’ area, air energy supply and electricity consumption are both decreased, while the CS is increased. An orthogonal method was used to find the optimal configuration. The configuration comprising 10 m² solar collectors and 5 kW heat pump, is determined to be the optimizing one. It has the minimum CS of 61,730 CNY. More details about the optimum system is shown in Tab.2.

![Figure 1: Schematic diagram](image1)

![Figure 2: Energy consumption of the system](image2)

![Figure 3: The CS of the system](image3)

| Solar collector areas /m² | capacity of heat pump /kW | SF | AF | CS /CNY | ICS /CNY | RICS |
|---------------------------|---------------------------|----|----|---------|----------|------|
| 10                        | 5                         | 0.34 | 0.38 | 61,730  | 25,000   | 0.405 |

The system is now considered at different cities of China. Tab.3 shows the annual average solar irradiation and outdoor temperature of the three considered cities. The climate condition (solar irradiation and outdoor temperature) vary from location to location. Beijing and Xi’an are belong to a typical north temperate zone semi-humid continental monsoon climate, which has four seasons, dry and windy spring, hot summer and rainy, cool quickly in the fall, winter cold and less snow. 60-80%
of the annual precipitation is concentrated in summer (from Jun to August). Annual average outdoor temperature of Beijing is lower than Xi’an. Due to sitting in the midwest region of China, Xi’an has lower rainfall and is dryer than Jinan and Beijing. Nanjing has a subtropical monsoon climate with abundant rainfall. In summer, it is hot and rainy. In the winter, it is wet and warm, while it seldom snows. Its average outdoor temperature is higher than the other two cities. Optimal simulations were repeated to carry out, in order to find the optimum configuration of each system in each location. Note that all discussions are based on the optimum configurations in the following subsections. Table 4 shows details of the optimal simulation results of three systems in Beijing, Xi’an, and Nanjing, respectively. For the results, we can see that: the optimal configuration of the combsystem in each city is the same, which has $10^2$ solar collectors and a 5kW heat pump. Beijing has the minimum cost (41,963 CNY), mainly because of the sum of $AF$ and $SF$ is the largest.

### Table. 3 Annual average solar irradiation and outdoor temperature

| City  | Latitude /° N | Longitude /° E | Sum of solar irradiation kWh/m²/year | Average outdoor temperature /°C |
|-------|---------------|----------------|-------------------------------------|-------------------------------|
| Beijing | 39.93         | 116.4          | 1481                                | 12.9                          |
| Xi’an  | 34.27         | 108.9          | 1263                                | 14.5                          |
| Nanjing| 32.05         | 118.78         | 1278                                | 16.2                          |

### Table. 4 Optimal simulation results in three cities

| City  | Solar /m² | Air /kW | SF  | AF  | CS /CNY | ICS /CNY |
|-------|-----------|---------|-----|-----|---------|----------|
| Beijing | 10        | 5       | 0.34| 0.38| 61,730  | 25000    |
| Xi’an  | 10        | 5       | 0.32| 0.41| 57,006  | 25000    |
| Nanjing| 10        | 5       | 0.32| 0.42| 50,194  | 25000    |

3.2. **Comparing the payback period of the renewable systems**

The payback time of each optimization system with respect to local traditional heating method is also counted in this study. Since 1950s, the central heating supply policy has been performed in cities north of the Huai River, which divides China into north and south regions [9-10]. Among the three cities, two cities have central heating, which are Beijing, and Xi’an. In Nanjing located in the south of China, there is no nonperformance of central-heating. Although the lowest temperatures is around 0°C, it’s still a bit cold in winter due to its high humidity. So, more and more family houses install gas hanging stoves to meet the demand of SH and DHW.

So, the traditional heating methods in three cities have been summarized shown in Table 5. For Beijing and Xi’an, gas hanging stoves are used to meet the demand of DHW, so, the cost of traditional heating method contains central heating fee, cost of the gas hanging stoves and nature gas fee. For Nanjing, the cost of traditional heating method contains cost of the gas hanging stoves and nature gas fee. The central heating for SH is charged according to per square (floor area). The latest price is 18 CNY for per square meter in heating season in Beijing, while that is 23.2 CNY in Xi’an. A cubic natural gas burning would emit 8MJ(10.6kWh). The cost per cubic natural gas is about 3CNY. Mark price of gas hanging stoves (both for DHW and SH) is 10,000CNY. Based on these values and the total energy consumption for each system, the investment and running costs for the three cities were calculated (list in Table.6).

The investment and running cost of the optimal configuration in each city are summarized in Table.7, in which the payback periods relative to traditional heating method in the five cities are also illustrated. The payback period was calculated as follows:

$$\text{payback period} = \frac{\text{investment cost of renewable system} - \text{investment cost of traditional heating method}}{\text{running cost of traditional heating method} - \text{running cost of renewable system}}$$
It can be seen that, the investment cost of the system is higher than that of traditional heating method in three cities. But, their running costs are much lower. Beijing has the longest payback period (15.9 years).

Table.5 The local traditional heating method for the three cities

|       | Beijing | Xi’an | Nanjing |
|-------|---------|-------|---------|
| SH    | central heating | central heating | natural gas |
| DHW   | natural gas     | natural gas     | natural gas |

Table.6 The cost of traditional heating methods for the three cities

|       | Beijing | Xi’an | Nanjing |
|-------|---------|-------|---------|
| Investment cost (CNY) | 3,000   | 3,000   | 10,000   |
| Running cost (CNY/year) | 3,665   | 4,445   | 3,293    |

Table.7 Payback periods relative to local traditional heating method

|       | Beijing | Xi’an | Nanjing |
|-------|---------|-------|---------|
| ICS (CNY) | 25,000   | 25,000   | 25,000   |
| RCS (CNY/year) | 2283     | 1967     | 1513     |
| Payback period (Year) | 15.9     | 8.8      | 8.4      |

4. Conclusions
Based on the analysis and comparison study, following conclusions are given. At Beijing, Xi’an and Nanjing, applied in a mid-sized single-family house to meet the energy demand of DHW and SH, the solar thermal and air source heat pump combined system comprising 10m² solar collectors and 5 kW air source heat pump is the best configuration having the minimum cost, but the minimum cost is different for each location. At Nanjing, the system gives the minimum cost of 50,194 CNY, meantime, has the shortest payback period for its lower running cost. While, the payback time of optimum system at Beijing is 15.9 years exceeding its running time, due to the lowest central heating fee included in the cost of the traditional heating method. Even so, its environmental protection can't be ignored.

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