Economic analysis of solar and air energy systems for energy demand of space heating and domestic hot water of buildings

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Abstract. This study focuses on the economy of two renewable systems supplying the same demand of domestic hot water (DHW) and space heating (SH) for a city household located in Beijing of China. The systems are the solar thermal system and air source heat pump system. Both the two systems are considered for meeting the energy demand of SH and DHW. Optimized simulations are carried out to recognize the most economical configurations. The results show that, for a 15-year running time, the air source heat pump system comprising a 10 kW air source heat pump is the best configuration and has the minimum cost.

1. Introduction
In China, with the increase in energy consumption, the issue of fossil fuel energy shortage poses a challenge to the sustainable economic development. Moreover, the sharp increase in gas pollutants (CO₂, NOₓ) has great influence on the environmental quality. The use of renewable energy resources is considered to be a key solution to reduce fossil fuel consumption and gas pollutant emissions in the long time. The energy demand in buildings accounts for approximately 27.8% of China’s energy budget[1]. In buildings, energy is supplied for heating, hot water, cooling, and lighting, and it is mainly produced by burning fossil fuels. To achieve low carbon emissions and save energy, the Chinese government is committed to promote the utilization of renewable energies in buildings[2-7]. In these circumstances, a growing number of households in China have renewable thermal systems for domestic hot water (DHW) and space heating (SH).

The solar thermal system is the main renewable energy technology for DHW and SH in buildings. Solar hot water achieved maturity in China since the 1970s. It has a large scale application in many provinces with relatively advanced economy, such as Guangdong, Zhejiang, Jiangsu, Shandong, Hebei, Anhui, Hubei, Guangxi, and Jiangxi[12-14]. Since the early 2000s, the solar thermal technology for SH is beginning to catch up in developed cities, such as Beijing and Shanghai[15, 16]. Since the early 2000s, the air source heat pump has been used in the warm southland of China to supply the energy demand of SH and DHW in buildings[17, 18], but its application is limited in the northern cold region of China. This is because the heating coefficient of performance (COP) of the air source heat pump decreases significantly as the outdoor temperature falls. Thus, numerous new technologies focus on improving the COP of the air source heat pumps used in cold regions, such as those changing the structure of the outside machine and the phase change energy storage technology[19-21]. With the new technologies, the air source heat pump for SH and DHW has been gradually applied in the northern regions of China, such as Harbin[22].

The solar thermal system and air source heat pump system are all low carbon emission systems. Different systems have different economic characteristics. Therefore, an economic analysis of the use
of these two systems to meet the same demand of SH and DHW from a city family house in Beijing of China is carried out. For each system, different sizes of the main components (solar collectors or air source heat pump) lead to different configurations of the system. The optimum configuration of each system is the one that has the minimum cost. The optimal simulation results of the two systems are explained in detail for discussion.

2. Optimization

The solar (air) energy resource is used through solar collectors (air source heat pump) to supply energy for the DHW and SH demand from a mid-sized single-family house located in city of Beijing, China. The DHW need is 200 L/d of water at 50 °C. The heated area of the building is 130 m². The indoor heating set temperature is 20 °C during the day and night in the heating period from November 1st until March 1st next year. Figure 1 shows the monthly averaged solar radiation and outdoor temperature in Beijing.

In the solar thermal system, solar collectors and an electric heater provide energy to the system. In air source heat pump system, the solar collectors are replaced by an air source heat pump. The total cost of a system (CS) is defined as

\[ CS = ICS + RCS \]  

where \( ICS \) is the investment cost of all system components, and \( RCS \) is the running cost of the system during the project life time.

\[ ICS = C_{\text{solar collector}} + C_{\text{tank}} + C_{\text{other components}} \]  

or

\[ ICS = C_{\text{air heat pump}} + C_{\text{tank}} + C_{\text{other components}} \]  

where \( C_{\text{solar collector}}, C_{\text{air heat pump}}, C_{\text{tank}}, \) and \( C_{\text{other components}} \) are the sum of the present value of solar collectors, air pump, water tank, and other needed components (such as water pumps and pipes), respectively, during the system lifetime. Considering that a mid-sized single-family house has less initial investment, \( ICS \) corresponds to the funds invested at the same time, without defining an annuity payment.

\[ RCS = Ecs \times N + MCS \]  

where \( Ecs \) is the annual total electricity consumption of the system. \( N \) is the project lifetime in years. \( MCS \) is the maintenance cost of the system, which is calculated as 1% of their \( ICS \). The present local market prices used for the CS are listed in Table 1.
Table. 1  Relevant factors used for the CS

| 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. Simulation results and analysis

The optimization of these two systems is achieved by using the Polysun software. In the simulation, the area of solar collectors or the capacity of the heat pump is increasing until there is no shortage of power supply to the energy demand of DHW and SH. The projected lifetime of each system is 15 years.

3.1 Solar thermal system

In this system, the solar collectors and an electric heater are used to supply energy for DHW and SH demand. The schematic diagram of this system is shown in Figure.2. The main components are solar collectors and the storage tank with a heater, which are both the energy supplies to the system. In the simulation, the area of solar collectors is increased until there is no shortage of power supply to the energy demand of DHW and SH. Many configurations with different areas of solar collectors that can meet the heating demand are considered. Each collector is facing to the south and tilted at 45°. The volume of the storage tank is 500 L.

In the simulation, only when the area of the solar collectors is increased to 10 m² there is no shortage of power supply to the energy demand of DHW and SH. Thus, we set the range of the area of solar collectors from 10 m² to 36 m². The solar energy supply and electricity consumption with different areas of solar collectors are shown in Figure.3, which shows that the larger the area of solar collectors, the less electricity consumption of the system. Among these configurations, the one that has the minimum cost (CS) of the system during the project lifetime is to be considered. Based on the values listed in Table. 1 and the total electrical energy consumption, the CS of the system is evaluated. Figure.4 shows the CS changes with the area of solar collectors. It shows that, for a project lifetime of 15 years, the optimum system comprises 32 m² of solar collectors and has the minimum CS of 85,422 CNY. More details about the optimum system are summarized in Table. 2. The solar collectors have the CS of the system, with 27.2%, and they generate 51% of the energy.

Figure.2 Schematic diagram of Solar thermal system
3.2 Air source heat pump system

In this system (shown in Figure 5), the heating demand has to be met by an air source heat pump and an electric heater. In this case, different capacities of the heat pump are taken into consideration. In the simulation, the capacity of the heat pump is increased until there is no shortage of power supply to the energy demand of DHW and SH. The minimal capacity is 10 kW. Thus, we set the range of the power of air heat pump from 10 kW to 35 kW. The air energy supply and electricity consumption with different capacities of air heat pumps are shown in Figure 6, which shows that there is a slight increase in the electricity consumption with increasing capacity of the heat pump. Therefore, the CS mainly depends on the price of the air source heat pumps for different configurations. Figure 7 shows the changes in CS with different capacities of air source heat pumps. It shows that, for a project lifetime of 15 years, the optimum system comprises a 10 kW heat pump and has the minimum CS of 78,355 CNY. More details about the optimum system are summarized in Table 7. The heat pump has the CS of the system, with 37%, and it generates 62% of the power.
Figure 6 Energy consumption of air source heat pump

Figure 7 CS of air source heat pump

| Capacity of air heat pump/kW | Energy consumption/kWh | Capacity of air heat pump/kW | CS/CNY ×10^3 |
|-----------------------------|------------------------|-----------------------------|---------------|
| 10                          | 0                      | 10                          | 80            |
| 15                          | 2                      | 15                          | 90            |
| 20                          | 4                      | 20                          | 100           |
| 25                          | 6                      | 25                          | 110           |
| 30                          | 8                      | 30                          | 120           |
| 35                          | 10                     | 35                          | 130           |

### 3.3 System comparisons

From Table 2 and Table 3, it can be seen that, for the city of Beijing, the investment cost of air source heat pump system, is higher than the solar thermal system. While, the total cost is the opposite in a running time of 15 years. So, the air source heat pump system, which comprises a 10 kW heat pump to meet the same energy demand of a city family house Beijing of China, has cost advantage owing to its minimum cost.

### 4. Conclusions

Based on the analysis and comparison study, the following conclusions are drawn. An economic analysis of the solar thermal system and air source heat pump system to meet the same energy demand of a city family house Beijing of China is carried out. For the solar thermal system, the configuration comprising 32 m² of solar collectors is the optimization one, which has the minimum CS of 85,422 CNY in the running time of 15 years. For the air source heat pump system, the configuration comprising a 10 kW air source heat pump is the best one, which has the minimum CS of 78,355 CNY in the running time of 15 years.

### References

[1] Liu, Z.; Guan, D.; Moore, S.; Lee, H.; Su, J.; Zhang, Q. Steps to China’s carbon peak. Nature 2015;522:279–81.
[2] Kevin, L. Critical review of China’s rapidly developing renewable energy and energy efficiency policies. Renewable and Sustainable Energy Reviews 2014;29:508-516.
[3] Li, J. F.; Wan, Y. H.; Ohi, J. M. Renewable energy development in China: resource assessment, technology status, and greenhouse gas mitigation potential. Apply Energy 1997;56:381-94.
[4] Liu, Y. N. A review of the renewable energy application in China. Constr Technol 2012;13:23–6 in Chinese.
[5] The Central People's Government of the People's Republic of China. Renewable Energy Law of PRC. Availableat: (http://www.gov.cn/ziliao/flfg/2005-06/21/content_8275.htm): June 21;2005.
[6] Yuan, X. L.; Wang, X. J.; Zuo, J. Renewable energy in buildings in China—A review. Renewable
and Sustainable Energy Reviews 2013; 24:1–8.
[7] Chen, Y. Design and operation methodology for active building- integrated thermal energy storage systems. Energy Build 2014; 84:575–85.
[8] Li, D.; He, J.; Li, L.A. review of renewable energy applications in buildings in the hot-summer and warm-winter region of China Renewable and Sustainable Energy Reviews 2016; 57: 327–336
[9] Lan, J. H. Study on the evaluation of energy efficiency performance for the local civil solar water heating system in Guangxi. Energy Sav Build 2012; 06:56–8 in Chinese.
[10] Qin, X. Y. Economic analysis concentrated solar hot water system of Guangxi. Sci Technol Innov Herald 2012; 23:189–90 in Chinese.
[11] Johnston, D. Solar energy systems installed on Chinese-style buildings Energy and Buildings 2007; 39: 385–392.
[12] Cui, Y. Performance analysis on a building-integrated solar heating and cooling panel. Renew Energy 2015; 74:627–32.
[13] Kelly, J. A.; Fu, M.; Clinch, J. P. Residential home heating: the potential for air source heat pump technologies as an alternative to solid and liquid fuels. Energy Policy 2016; 98:431–42.
[14] Shen, M.; Song, Z. Applicability of air-source heat pumps in colder climate and relevant measures. Heating Ventil Air Condition 2002; 32:37–9 in Chinese.
[15] Yu, L.; Ma, G.; Xu, R. Current status and development of low temperature air source heat pump. Constr Conser Energy 2007; 35:54–7 in Chinese.
[16] Zhang, Q. L.; Zhang, L.; Nie, J. Z.; Li, Y. L. Techno-economic analysis of air source heat pump applied for space heating in northern China Applied Energy 2017; 207:533–542.
[17] Li, Y.; Yu, T.; Chen, T. Energy efficiency and applicability of air-source heat pump floor radiant heating system in the northern cold areas. Heat Ventil Air Condition 2012; 42:62–5 in Chinese.
[18] Zhang, Y.; Ma, Q.; Li, B. Application of an air source heat pump (ASHP) for heating in Harbin, the coldest provincial capital of China. Energy Build 2017; 138:96–103.