A performance comparison of serial and parallel solar-assisted heat pump heating systems in Xi'an, China

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Abstract
In this study, a TRNSYS model for a solar-assisted heat pump (SAHP) water heating system for a university bathroom in Xi'an was developed and validated through experimental measurements. Under the typical meteorological conditions in Xi'an, a comparative analysis of the performance of the serial indirect expansion SAHP (IDX-SAHP) system and the parallel IDX-SAHP system during different seasons was conducted using the validated model. The results demonstrated that for annual operation, the parallel IDX-SAHP system showed better performance in the Xi'an district compared to the serial system. Under the same heating load, the average coefficient of performance (COP) of the serial IDX-SAHP system was 3.23 and that of the parallel IDX-SAHP system was 4.34. In particular, during summer and the transition season, the parallel IDX-SAHP system showed large advantages, mainly owing to a larger part of the heating load being provided by the solar collector. However, the serial IDX-SAHP system showed a higher efficiency than that of the parallel IDX-SAHP system during winter conditions.

KEYWORDS
COP, solar energy, solar-assisted heat pump, TRNSYS, water heating system

1 | INTRODUCTION

Energy is the material basis for human survival and social development. However, energy shortages have become a major problem throughout the world. In commercial buildings, the energy required for a hot water supply is the fourth highest consumption, behind that of heating, air conditioning, and lighting. In the United States, nearly 40% of households adopt electricity to heat water, which accounts for 17% of the total residential energy consumption.1 As an eco-friendly technology that uses renewable energy, heat pump technology has been applied in developed countries for many years.

This technology pumps low-grade heat into high-grade thermal energy and provides the heating load to users. With its high energy efficiency and low environmental pollution, air source heat pumps (ASHPs), ground source heat pumps, and solar energy heat pumps have been widely used and promoted as a new energy-saving technology.2-4 Thus, heat pump technology is an efficient heating method with a potential to replace conventional electric water heating systems.5

The ASHP system has been widely studied and applied in China. However, there are some disadvantages in its application. With low ambient or evaporation temperature, the evaporation side is prone to frosting, greatly reducing the COP of
the ASHP. On the other hand, solar radiation has been used as an important energy source for future development due to the advantages of easy access, low operating cost, and less impact on the environment. Considering the aforementioned reasons, the concept of a SAHP system that combines solar energy and a heat pump was proposed, not only overcoming the low density and instability of solar energy but also offsetting the low operation efficiency of heat pump under cold conditions. Therefore, the SAHP system can significantly save energy in buildings. Compared to conventional solar water heaters, the SHAP system provides high-temperature water in an efficient manner and therefore effectively reduces the collector area. Sun et al investigated the performances of an SAHP system and an ASHP system during different seasons; the results showed that the former performs better than the latter. Moreover, a large number of studies have found that the optimized SAHP system can operate stably at night, under completely overcast conditions or in countries and regions that lack solar radiation. According to the coupling mode of the solar collector and evaporator, the SAHP system can be distinguished into direct expansion SAHP (DX-SAHP) and indirect expansion SAHP (IDX-SAHP) systems. Morrison et al and Lerch et al found that the DX-SAHP system has a higher evaporation temperature and a longer collector lifetime than that of the IDX-SAHP system. Furthermore, the refrigerant of DX-SAHP system directly flows inside the solar collector, eliminating heat losses from the intermediate heat exchanger. However, due to its long refrigerant circulation loop, it may cause refrigerant leakage and trapping of the refrigerant in the evaporator and condenser. In addition, the DX-SAHP system is seriously affected by solar radiation, leading to performance differences among different regions. Consequently, the IDX-SAHP system has gradually become the focus of research. The IDX-SAHP system can be classified into three different categories: serial, parallel, and complex systems.

Sterling and Collins conducted comparative research among an IDX-SAHP system, a conventional solar collector system, and an electric water heating system; the results suggested that the IDX-SAHP system is the most energy efficient with the lowest operational cost among the three systems. Compared to the serial IDX-SAHP system, one advantage of the parallel IDX-SAHP system is that the solar collector and the heat pump work separately, guaranteeing the reliability of the hot water supply in case one of the two parts fails. Another advantage is that the solar collector can provide a large amount of heat when solar radiation is abundant, particularly under summer conditions. Meanwhile, the thermal performance and operational stability of the parallel IDX-SAHP system are better than those of the serial system. Panaras et al proposed a validated theoretical model for a parallel IDX-SAHP system and found that compared to a solar domestic hot water system, 70% energy saving could be achieved by the parallel system under Athens meteorological parameters, and the COP was 2.3. Although a parallel IDX-SAHP system uses both solar energy and outdoor air as dual heat sources, its performance will degrade under certain conditions, sometimes being even lower than that of the serial system. Kaygusuz established mathematical models of both serial and parallel IDX-SAHP systems and investigated them via experiment measurement and theoretical analysis. The experimental results demonstrated that during the heating season, that is, from November to April, the average COPs of serial and parallel systems are 4.0 and 3.0, respectively. The higher COP of the serial system is because in this system the solar collector serves as the evaporation heat source of the heat pump, ensuring a stable and suitable evaporating temperature for the heat pump under conditions with sufficient solar radiation. Therefore, the serial system can achieve stable operation even in a low-temperature environment. The complex IDX-SAHP system is also termed a dual source system and integrates the series and parallel systems. Thus, this system can draw energy from either the solar thermal storage or the atmosphere. Due to the complicated configuration and the matching relationship between components, this system has a higher initial cost and a higher control requirement to achieve good performance.

At present, SAHP system performance studies are typically conducted in a specific environment. Due to the different matching relationships between the environment and the heat pump system, the experimental results obtained among different regions are quite different. For building climate demarcation in China, they can be broadly divided into five zones: the severe cold, cold, hot summer/cold winter, hot summer/warm winter, and temperate zones. For the hot summer/warm winter zone, there is frequent rain and a relatively low ambient temperature during winter, which would have adverse effects on the heating power and the COP of a heat pump system. Li investigated the performance of a DX-SAHP system in the city of Shanghai and found that the system could meet the hot water demand of users during rainy days, although with modest performance. Thus, the DX-SAHP system is suitable for Shanghai due to its performance and simple structure. Xiao studied the distribution of sunshine radiation in Wuhan city and found that the complex system is suitable for this region and could work normally no matter if cloudy or during the night. For the cold zone, Ma examined the climate parameters in Tianjin, where the minimum ambient temperature is −11°C and the average temperature is −4.9°C during the coldest month. The results indicated that the serial SAHP system should be applied, with a COP of 2.4-3.27, during the heating period. From the aforementioned literature, it can be seen that in different climatic regions, sometimes even in the same region (such as Shanghai and Wuhan), the optimal system differs. Given the location of Xi'an, which
is at the transition of the cold zone and hot summer/warm winter zone, the optimal systems for the other cities in the cold zone do not apply to Xi’an. However, although many research studies regarding the SAHP system have been conducted on several aspects, the performance of the SAHP system in Xi’an district has not been fully studied. Thus, it is necessary to investigate a suitable system for the Xi’an region. Based on the hot water supply system of a university bathroom in Xi’an, the performance of the SAHP system during different seasons and throughout the year was examined using TRNSYS simulation. Using the established serial and parallel IDX-SAHP system models, the optimal operational mode of the SAHP system for the Xi’an district was obtained, which can provide a reference for the practical engineering design of the SAHP system.

2 | EXPERIMENTAL INVESTIGATION

2.1 | System descriptions

The schematic diagrams of the serial and parallel systems are shown in Figure 1.

For serial system (as shown in Figure 1A), it mainly consists of the solar collectors, heat storage water tank (HSWT), water source heat pump (WSHP), and consumer side water tank (CSWT). The solar collectors heat the water in the HSWT that serves as the evaporation source for the WSHP; thus, the water in the CSWT can be heated to the target temperature under a higher evaporation temperature. For parallel system (as shown in Figure 1B), the main components are the solar collector, the ASHP, and the CSWT. The water in the CSWT is simultaneously heated via the solar collector and the ASHP.

2.2 | Design parameters of the serial system

This study aimed at a hot water supply system of a university bathroom, wherein 60 tons of water in the CSWT needed to be heated to 50°C from 8:00 to 18:00 each day. Therefore, the daily heating load was approximately 10² kWh. The minimum temperature during winter in Xi’an is <0°C; thus, it is necessary to consider the antifreezing capability of collectors and pipelines. Evacuated collectors were adopted in this study. Furthermore, the average daily solar radiation during the coldest month (January) in Xi’an is 9937 KJ/(m²·d), with a southern direction and a tilt angle of 59°30; according to the research results proposed in previous studies, the heat COP was 2.8 while the collectors efficiency was 65%. In this case, to satisfy the daily heating load of 10² kWh, the theoretical collected heat amount of the solar collectors should be 5.6 × 10⁸ KJ/d. The area of the solar collector could be obtained using the following equation:

\[ A_c = \frac{Q_u}{I_c \eta_c} \]  

where \( Q_u \) is the daily heat collection of the solar collector, \( I_c \) is the average daily solar radiation during the coldest month, and \( \eta_c \) is the collector efficiency.

The area of the calculated collectors was 860 m² using Equation 1, consisting of 60 sets of MK-58-1800-50-2-1-83-20 evacuated collectors, as shown in Figure 2. Considering that a low evaporation temperature may exist, a mixture of alcohol and water (volume ratio of 1:2 and freezing point of \(-14.2^\circ C\)) was used as an antifreeze fluid to replace water as the heat medium. In the serial system, the HSWT was the evaporation heat source of the WSHP evaporator, which could offset the instability and discontinuity of the solar energy. Considering the influence of the occupied area and the heat dissipation, a cylindrical accumulator was used as the HSWT. The volume of the water tank was generally related to the daily amount of heat collection, heat absorption capacity of the heat pump evaporator, and property of the heat medium. The volume of the HSWT was determined using the following equation:

\[ V = \frac{Q_s}{(\rho c)_w \Delta t (1-\eta_s)} \]

where \( Q_s \) is the daily heat storage capacity, \( (\rho c)_w \) is the volumetric heating capacity of the heat medium, \( \Delta t \) is the temperature difference of the heat medium, °C; and \( \eta_s \) is the heat loss rate of the heat medium.

According to the typical meteorological parameters during January, it was found that during approximately two-thirds of the daytime, the solar radiation was sufficient. Then, during the remaining one-third of the daytime, the heat needed by the WSHP evaporator needed to be supplied by the HSWT. Consequently, the daily heat storage capacity was calculated to be 2.22 × 10⁸ KJ/d. In view of the previous research, the temperature difference of the heating medium is generally 10-15°C while the heat loss rate of the heat medium is 20%-40%. Thus, in this study, the temperature difference and the heat loss rate of the heat medium were 12°C and 20%, respectively. Finally, the HSWT volume was 55 m³ using Equation 1. Considering the economy and durability of the tank, the main structure of the tank was welded with 3-mm-thick steel plate, the shell of the tank was composed of a 1.2-mm-thick steel plate, and the whole water tank was thickened with a 200-mm insulation layer.

For the serial IDX-SAHP system, the WSHP provided the daily heat demand of 10² KJ by running for 10 hours. Therefore, the heating power of the heat pump was 278 kW. According to the capacity of the heat pump and the working range of the evaporation, two RW210-F WSHPs were adopted, each with an input power of 48 kW and a circulating water flow rate of 20 T/h.
Due to the low ambient temperature during winter conditions, the performance of both the ASHP and solar collector was low. Considering a certain heating load and the system stability, the ASHP should be selected in accordance with the minimum monthly average temperature. In this study, the minimum monthly average temperature in Xi’an was −3°C, and the heating power was 278 kW; thus, five DKFXRS-64II
ASHPs were selected, as shown in Figure 3. The input power was 19 kW and the circulating water flow rate was 12 T/h for each.

Jiang et al.\textsuperscript{35} examined the relationship between the collector area and the system initial investment of a parallel system during different months and found that the collector area can be designed according to the typical average daily radiation of the transition season. For Xi’an area, the typical average daily radiation during the transition season is 15 000 kJ/(m\textsuperscript{2}·d).\textsuperscript{30} Consequently, the area was 1025 m\textsuperscript{2} using equation . However, in this experiment, the serial and parallel systems shared the same collectors. Given the investment,\textsuperscript{36} the collector area was designed to be 860 m\textsuperscript{2}.

2.4 | Measurement instrumentation

The water temperature and the flow rate were tested by placing sensors at the component inlets and outlets. According to the temperature measuring range and the measurement error, a copper-constantan (T-type) thermocouple was adopted. In addition, the temperature correction coefficient was obtained through calibration. The total solar radiation projected onto the collectors was measured using a TBQ-2 pyranometer with a sensitivity of 7-14 μV/(W·m\textsuperscript{2}), a response time of <30 s, and a measuring range of 0-2000 W/m\textsuperscript{2}. The installation angle of the pyranometer was consistent with the angle of the

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**FIGURE 2** Evacuated collectors

**FIGURE 3** Air source heat pumps

**FIGURE 4** Measuring instruments. A, HP34970A data collector; B, TBQ-2 pyranometer; C, YB-70H handheld ultrasonic flowmeter; and D, DF-type centralized electric energy meter
collector. Moreover, two layers of quartz glass cover, created via optical cold processing, were needed to reduce the influence of environmental changes on equipment performance. The flow rate was measured using a YB‐70H handheld ultrasonic flowmeter, with a diameter range of 10‐6000 mm and a velocity range of 0‐30 m/s. The real‐time experimental data were recorded using a HP34970A data collector. Afterward, the power consumption of the heat pump compressor, water pump, fan coil unit, and the other electrical components was measured using a DF‐type centralized electric energy meter. The measuring instruments are shown in Figure 4.

In this study, the uncertainty analysis method put forward by Moffat was adopted. Assuming the variant \( R \), which is calculated from a set of independent variants \( X_1, X_2, \ldots, X_n \), that is to say \( R = R(X_1, X_2, \ldots, X_n) \), the uncertainty of the variant \( R \) can be determined by combining the uncertainties of individual terms and can be expressed as follows:

\[
\delta R = \left[ \sum_{i=1}^{n} \left( \frac{\partial R}{\partial X_i} \delta X_i \right)^2 \right]^{1/2}, \tag{3}
\]

where \( \delta R \) is the total uncertainty of the experimental result \( R \) and \( \delta X_i \) is the uncertainty of the independent variant \( X_i \). The water temperature is a directly measured variable; thus, the uncertainty of a measurement result was determined by the standard deviation of the arithmetic average value of the records. Thus, the maximum measurement uncertainty for water temperature was found to be 1.7%.

3 | MODELING

TRNSYS is a complete and extensible simulation tool for system transient simulation, including solar energy systems, heat pumps, ice storage systems, and other renewable energy systems. In this study, TRNSYS software was used to model serial and parallel IDX‐SAHP systems to investigate the operating efficiency, heating capacity, and energy consumption of the SAHP systems.

3.1 | Models of serial and parallel modes

The main component types used in this simulation are listed in Table 1, in which the evacuated collector and the heat pump modules need to run with the user’s source files while the other modules only need the corresponding input and output parameters. For the evacuated collector, the absorptivity was influenced by the solar direction; thus, it was necessary to obtain the modified coefficients of different two-dimensional incident angles. According to the modified coefficients of the two-dimensional incident angle in Xi’an, the parameters of the evacuated collector were corrected. For the heat pump, the COP was influenced by the evaporation and condensation temperatures. Based on the heat pump performance curves of RW‐210F and DKFXRS‐64II provided by the manufacturers, which illustrated the relationship of the COP with the evaporation and condensation temperatures, the heat pump module could be established. The details of the water pumps are shown in Table 2. Owing to the fixed frequency, the flow rates of the water pumps were constant.

Figure 5 shows the TRNSYS model of the serial IDX‐SAHP system. The system was mainly composed of an evacuated collector, a HSWT, a WSHP, a CSWT, a control system, an output module, and a display module. The system first loaded the meteorological data of the Xi’an area by Type 109 and then transmitted them to the evacuated collector (Type 538) as the input environmental parameters. The evacuated collector heated the water storage tank (type 4‐2), while its running time was controlled by the time controller Type 14. The HSWT acted as the heat source for the WSHP (Type 668) to provide the required heat for the evaporator; the heating

| TABLE 1 | Components used in the TRNSYS simulation |
|----------|------------------------------------------|
| Component | TRNSYS type |
| Weather data reader | 109 |
| Evacuated collector | 538 |
| HSWT | 4 |
| CSWT | 4 |
| WSHP | 668 |
| Water pump | 3 |
| Load profile | 14 |
| Results | 24 |
| Printer | 25 |
| Graphic plotter | 65 |
| ASHP | 665 |
| Mixer | 11 |
| Fan | 3c |

| TABLE 2 | Water pumps used in the serial and parallel systems |
|----------|--------------------------------------------------|
| Flow (m³/h) | WSHP water pump | ASHP water pump | Evacuated collector water pump |
| 20 | 4.48 | 43 |
| Power (kW) | 0.8 | 0.175 | 2.25 |
| Head (m) | 9 | 10 | 15 |
| Velocity (m/s) | 1.2 | 1.8 | 1.6 |
**FIGURE 5** TRNSYS model of the serial mode

**FIGURE 6** TRNSYS model of the parallel mode
time of the WSHP was also controlled by the time controller. Water with an initial temperature of 10°C was poured into the CSWT by the load profile (Type 14) prior to 8:00 each day. When the water temperature in the CSWT reached 50°C, the whole system was stopped by the temperature controller (Type 2b). The results were shown online by Type 65 or exported to a file. In addition, the energy consumption and efficiency of the system were calculated by the integrator (Type 24) and finally output to the corresponding text file.

Figure 6 shows the TRNSYS model of the parallel IDX-SAHP system. The system was mainly composed of an evacuated collector, an ASHP, a CSWT, a control system, an output module, a display module, etc. The system loaded meteorological data such as temperature and solar radiation of Xi'an area by Type 109 and simultaneously transmitted it to the evacuated collector (Type 538) and the ASHP (Type 665). The ASHP and the collector heated the water in the CSWT (Type 4) in parallel. The running times of the heat pump and the collector were controlled by the time controller (Type 14). Water with an initial temperature of 10°C was poured into the CSWT by the load profile (Type 14) before 8:00 each day. Once the temperature of the CSWT reached 50°C, the whole system was stopped by the temperature controller (Type 2b). The work processes of the output module and the display module were similar to those of the serial system.

3.2 | Model validation

To ensure the validity of the models, the modules of the WSHP, ASHP, and evacuated collector were validated by experiments, respectively, before system simulation. The CSWT was filled with 60 tons of cold water (10°C) before 8:00 and then heated. The meteorological parameters during the experiment are shown in Figure 7.

The experiment on the performance of the solar collector was conducted on January 8. Figure 8A shows the measured and simulated hourly water temperatures in the CSWT. It was found that the simulated result generally fits well with the measurement data, except during the time period from 8:30 to 9:30, during which the temperature variation trends under experiment and simulation were not consistent. The main attribution was that the high-temperature water remaining from the previous day resulted in a measurement data increase first and then a decrease. The experiment on the performance of the WSHP was conducted on January 11. Two WSHPs simultaneously heated the water. Figure 8B shows the good agreement between the simulation values and experimental results, proving the validity of the simulated WSHP module. The experiment on the performance of the ASHP was conducted on February 19. Five ASHPs simultaneously heated the supplied water. Figure 8C shows that the experimental results agreed well with the simulation values before 13:00. However, the water temperature values under the experiment were lower than those under simulation after 13:00, which was probably a result of the direction and location of the ASHPs. Because the ASHPs were shaded by buildings, the actual ambient temperature around them was slightly lower than the meteorological data during the afternoon. Based on the module validation of the solar collector, WSHP, and ASHP, the performance of the SAHP system was studied.

4 | RESULTS AND DISCUSSION

In this study, the representative days during a typical meteorological year\(^4\) for summer, winter, and the transition season was selected for performance investigation. The daily energy consumption, heating capacity, and COP values were adopted to compare the two systems. For the serial IDX-SAHP system, the daily heating load was provided by the WSHP. The energy consumption was mainly caused by the WSHP compressor and the water pumps of the HSWT, CSWT, and solar collector. For the parallel IDX-SAHP system, the heating load was separately provided by the solar collector and the ASHP. The energy consumption was mainly generated by the ASHP compressor and the water pumps, which were equipped at the CSWT and the solar collector. The COP of the system was defined as the ratio of the thermal energy output to the power consumption of the system\(^4\) as follows:

\[
\text{COP} = \frac{Q_w}{W_{\text{comp}}}.
\]

where \(Q_w\) is the thermal energy output, \(W\) and \(W_{\text{comp}}\) is the power consumption of the system, \(W\).

4.1 | Summer operational condition

First, August 1 to August 7 during a typical meteorological year in Xi'an were selected as the representative weather
days to simulate the summer operational conditions. Figure 9 shows the meteorological parameters from August 1 to August 7. Figure 10 shows the simulated results of the serial and parallel systems in terms of system energy consumption, system heating capacity, and COP value.

Combined with the meteorological parameters shown in Figure 9, from Figure 10A, it is apparent that the energy consumption of the serial IDX-SAHP system was much higher than that of the parallel system during summer when both the solar radiation and the ambient temperature are sufficient. Compared to the WSHP and ASHP systems, the water pumps consumed very limited energy. This indicates that the energy consumption of the serial and parallel systems is mainly influenced by the WSHP and ASHP, respectively. As shown in Figure 10C, the average COP of the serial system was 4.87, which was much lower than that of the parallel system. On August 4 (corresponding to 5160-5184 hours in Figure 9), with a low ambient temperature but a high solar radiation, the SAHP system, particularly the parallel system, could still run at a high COP. The results suggest that the solar radiation can improve the energy efficiency of the SAHP system even when the ambient temperature is unsatisfactory, which means that the performance of the SAHP system is influenced by the combined effect of the ambient temperature and solar radiation. In addition, from Figure 10B, it is apparent that for the parallel system, in most cases, the heat supplied by the solar collector accounted for >80% of the total heating capacity of the system, except for the day on August 7, during which the heat provided by the solar collector accounted for 70.38% of the total system heating capacity. This was due to the low ambient temperature and solar radiation on that day. This phenomenon indicates that for the parallel IDX-SHAP system, the solar collector can provide the main heating load of the system under a condition of adequate solar radiation. In this situation, the number of running ASHPs can be somewhat reduced.

Figure 11 shows the outlet temperatures of the different components of the serial and parallel systems. In Figure 11(a), it was found that for each day, the outlet water temperature of the WSHP first reached and then exceeded 50°C, and then decreased (such as during the period of 5120-5140 hours). This was because the heat pump stopped running once the
Due to the heat loss to the ambient conditions, there was a slight reduction in the temperature of the CSWT. The outlet water temperature of the HSWT was between 13 and 20°C, corresponding to the evaporation temperature of the WSHP. Similarly, as shown in Figure 11B, the outlet water temperature of the ASHP could also satisfy the users’ requirement for hot water. However, for the parallel system, the evaporation temperature was directly related to the ambient temperature, which was significantly higher than the evaporation temperature of the WSAP under the serial system. In addition, the maximal outlet temperature of the evacuated collector was nearly 65°C, providing abundant thermal energy for the parallel system. Because the energy consumption of the solar collector was much lower than that of the ASHP system, the parallel SAHP system could operate in an efficient manner under sufficient solar radiation, showing great advantages. The aforementioned results further show the reason for the performance difference between the parallel and serial systems under summer conditions.
4.2 | Transition season operational condition

For the transition season, April 21 to 27 were selected as the typical weather days for system performance investigation. Figure 12 shows the meteorological parameters during a typical transition season. Through the simulation and energy analysis, the energy consumption, heating capacity, and COP values of the two systems were obtained, as shown in Figure 13.

As shown in Figure 13A, the energy consumption of the serial SAHP system was generally twice that of the parallel system. The power consumption of the water pumps accounted for a fraction of the total energy usage under these two systems.

In addition, as shown in Figure 13B, it was found that on April 23 and April 25, the heat supplied by the solar collector accounted for 49.69% and 45.10% of the total heating capacity of the parallel system, less than that supplied by the ASHP. This was mainly due to the low ambient temperature and solar radiation rate on these 2 days of 4859.32 and 4414.07 MJ, respectively. This suggests that with deterioration in the environmental condition, the proportion of the heat output of the solar collector decreased, which subsequently caused a reduction in the COP of the parallel system. However, under transition season conditions, the COP of the parallel IDX-SAHP system was still higher than that of the serial system, as shown in Figure 13C, wherein the COP of the parallel system was generally 6.0-8.0, while that of the serial system was approximately 3.0-4.0.

Compared to the summer conditions, the outlet temperatures of the HSWT (Figure 14A) and evacuated collector (Figure 14B) decreased during the transition season, resulting in performance degradation of the serial and parallel systems. Under the serial system, the outlet water temperature of the HSWT, which was strongly linked to the evaporation temperature of the WSHP, was only approximately 10°C (Figure 14A). However, under the parallel system, the evacuated collector could still provide considerable thermal output (Figure 14B). In addition, as shown in Figure 12, in most cases, the ambient temperature was at a relatively high level (10-22°C), ensuring an acceptable evaporation temperature for the ASHP. The aforementioned factors allowed the parallel system to maintain a comparatively good performance.
and therefore show better advantages than those of the serial system during the transition season.

### 4.3 Winter operational condition

Under winter conditions, January 11 to 17 were selected as the typical weather days. Figure 15 shows the meteorological parameters of these days. The performance comparison of the parallel and serial systems is shown in Figure 16.

Figure 16A shows that the energy consumption of the serial system was lower than that of the parallel system under winter conditions, which was in contrast to summer conditions and transition season. Meanwhile, for the parallel system, the proportion of the heat provided by the solar collectors decreased, as shown in Figure 16B. For example, on January 13, the ratio of the heat output of the solar collectors to the total heat output of the parallel system decreased to 25.34%. In this case, the heating load of the parallel system was mainly supplied by the ASHP system, leading to an obvious increase in system energy consumption and a reduction in energy efficiency. The aforementioned circumstances finally resulted in a decreased COP for the parallel system. Figure 16C shows that during the period January 11 to January 17, the average COP of the parallel system was 2.51 and that of the serial system was 3.00. The reason is evident in Figure 17, in which the outlet temperatures of the main components of the serial and parallel systems under winter conditions are shown.

In Figure 17B, the outlet temperature of the solar collector was approximately 0-20°C each day, resulting in a limited contribution to the heat supply of the parallel system. Meanwhile, the ASHP was operated in a low-temperature environment, sometimes even below 0°C (corresponding to the ambient air temperature shown in Figure 15). These two main factors seriously degrade the system's efficiency performance. However, for the serial system, the outlet water temperature of the HSWT was near 10°C, with little fluctuation (Figure 17A), providing a stable and relatively appropriate evaporation temperature for the WSHP. As a result, under winter conditions, the serial system shows a better performance than the parallel system.

### 4.4 Annual operational condition

The aforementioned results in this study illustrate that the series and parallel IDX-SAHP systems present different
advantages under different climatic conditions. Based on the typical meteorological year weather data of Xi’an, the annual energy consumption and COP analysis of the two systems were examined. The simulated results are shown in Figure 18. It was found that for annual operation in Xi’an, the energy consumption of the serial system was $1.2 \times 10^3$ GJ, obviously higher than that of parallel system, with a value of $0.89 \times 10^3$ GJ. The annual average COPs of the serial and parallel systems were 3.23 and 4.23, respectively, suggesting that under the annual condition, the parallel IDX-SAHP system is more suitable for application in the Xi’an region.

5 | CONCLUSIONS

In this study, TRNSYS software was used to investigate the performances of both serial and parallel IDX-SAHP systems.
The relevant components of the models were validated by experimental measurement. Based on the typical meteorological parameters of the Xi'an district, the energy consumption, heat capacity, and COP values of the two systems under different weather conditions were examined. Several conclusions can be made as follows:

1) Under the summer and transitional season conditions, due to the satisfied ambient temperature and solar radiation, the parallel system shows higher energy efficiency than the serial system under the same heating load. For the parallel system, with the increase in the ambient temperature and enhancement of solar radiation, the ratio of the heat output of the solar collectors to the total system heating load showed an increasing trend.

2) During winter, for the parallel system, the performances of both the solar collectors and the ASHP will decrease due to the adverse weather conditions, resulting in a large increase in energy consumption and a reduction in system efficiency. However, for the serial system, because the heat output of the solar collector is used as the evaporation heat source of the WSHP, the stable operation of the serial system is ensured; thus, the serial system has a higher COP than that of the parallel system.

3) The annual energy consumption of parallel system is 894 GJ, with an average COP of 4.34. The annual energy consumption of the serial system is 1200 GJ, with an average COP of 3.23. For year-round operation, the parallel IDX-SAHP system has better energy efficiency performance than the serial system, indicating that the parallel system is more suitable for year-round operation in the Xi'an district.

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NOMENCLATURE

SAHP   solar-assisted heat pump
IDX-SAHP indirect expansion solar-assisted heat pump
DX-SAHP direct expansion solar-assisted heat pump
COP   coefficient of performance
ASHP   air source heat pump
WSHP   water source heat pump
HSWT   heat storage water tank
CSWT   consumer side water tank
\( \delta R \)  the total uncertainty of the experimental result \( R \)
\( \delta X_i \)  the uncertainty of the independent variant \( X_i \)
\( A_c \)  area of the solar collector
\( Q_u \)  heat collection of the solar collector
\( I_c \)  average daily solar radiation in the coldest month
\( \eta_c \)  collector efficiency
\( V \)  volume of the HSWT
\( Q_s \)  daily heat storage capacity
\( (\rho c)_w \)  volumetric heat capacity of the heat medium
\( \Delta t \)  temperature difference of the heat medium
\( \eta_s \)  heat loss rate of the heat medium
\( Q_w \)  thermal energy output
\( W_{\text{comp}} \)  power consumption of the system

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