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Technical article

Investigation of the Influence of Cross-Seasonal Heat Replenishment by a Cooling Tower on the Operational Characteristics of a Heating-Only Ground-Source Heat Pump System

Qinhan Guo [1]*, Yan Li [1], Qianchang Li [1], Wenke Zhang [1]*, Shanshan Zhang [2], Zhaoyi Zhuang [1] and Jie Liu [3]

[1] *School of Thermal Engineering, Shandong Jianzhu University, Jinan 250101, China.*
[2] *Shandong Zhongrui New Energy Technology Co, Jinan 250101, China.*
[3] *China Construction Industrial & Energy Engineering Group Co., Ltd., China.*

ABSTRACT

To address soil cold accumulation in heating-only ground-source heat pump (GSHP) systems, this study proposes a cooling tower-assisted cross-seasonal heat replenishment method during the non-heating period. A residential district in Weifang was selected as the case study, and simulation models of both a heating-only GSHP system and a cooling tower-assisted hybrid GSHP system were established in TRNSYS. The long-term variations in soil temperature, borehole outlet water temperature, unit coefficient of performance (COP), and total system energy consumption were analyzed. In addition, two control strategies, namely time-based control and wet-bulb temperature difference control, were compared. The results show that cross-seasonal heat replenishment by the cooling tower can effectively slow the decline in soil temperature and improve the long-term operating conditions of the GSHP system. After 10 years of operation, the soil temperature of the hybrid system remained above 14 °C. Compared with the time-based control strategy, the wet-bulb temperature difference control strategy resulted in lower total system energy consumption, while both strategies maintained relatively stable heat pump performance. Under the conditions considered in this study, Strategy A4 showed a comparatively better overall balance between underground thermal maintenance and long-term energy consumption. These results provide a reference for the retrofit and operation optimization of heating-only GSHP systems in cold regions.

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1. INTRODUCTION

The As the proportion of building energy consumption in global energy use continues to increase, ground-source heat pump (GSHP) systems have become an important low-carbon technology for building heating and

* Corresponding authors. Email addresses: qh17660108195@163.com (Qinhan Guo) wenkezhang2006@163.com (Wenke Zhang)

cooling because of their high energy efficiency, stable operation, and low emissions (Liu, et al. 2019; Raheem, Zheng and Wood 2026a). However, the long-term performance of GSHP systems depends strongly on underground heat exchange conditions. Continuous imbalance between heat extraction and heat rejection may lead to soil temperature drift and deterioration of unit performance (Lin et al. 2026), which has become a key bottleneck restricting the sustainable and efficient operation of GSHP systems and threatening their long-term economic and environmental benefits.

In some renovated urban residential communities in China, GSHP systems are used only for winter heating, whereas split air conditioners are adopted for independent cooling in summer. Under such a heating-only operating mode, heat is continuously extracted from the soil during the heating season, while effective heat replenishment is absent during the non-heating period. This results in a year-by-year decline in soil temperature, a reduction in system COP, and, in severe cases, instability in system operation (Li and Hu 2022). In recent years, under the "dual carbon" goals and the green, low-carbon transition of the building sector, building energy systems have increasingly emphasized not only energy saving and consumption reduction, but also long-term operational stability, sustainable resource utilization, and coordinated environmental benefits. Therefore, alleviating underground thermal imbalance while meeting heating demand has become an important topic in the sustainable utilization of geothermal energy (Raheem, Zheng and Wood 2026b).

To address thermal imbalance on the ground side, cross-seasonal heat replenishment has been considered a feasible improvement approach. In previous studies, solar energy has often been used as the primary heat source for cross-seasonal heat storage (Sun et al. 2025). Although solar-assisted heat replenishment has the advantages of being clean and renewable, it still faces several limitations in practical engineering applications. On the one hand, the initial investment is usually high, and the required installation area is relatively large, which restricts its application in residential districts with dense buildings or limited roof resources. On the other hand, its performance is strongly affected by solar radiation, day-night variation, and cloudy or rainy weather. By contrast, ambient air is widely available as a heat source and can be utilized in a more flexible manner. Heat can be extracted through either direct-contact or indirect-contact heat exchange equipment, with less dependence on installation conditions and greater flexibility in equipment arrangement.

Based on this, some researchers have attempted to couple cooling towers with GSHP systems to achieve underground heat replenishment during the non-heating period or transitional seasons. Wen et al. (2011) analyzed the auxiliary heating capacity of cooling towers during the transitional season and showed that, under suitable air-state conditions, cooling towers can provide a certain amount of heat, thereby demonstrating the feasibility of auxiliary heat replenishment. Ge et al. (2025) established a heat and mass transfer model for an open cross-flow cooling tower and determined the optimal liquid-to-gas ratio for soil heat replenishment by varying the mass flow ratio of inlet humid air to solution, thus providing a basis for optimizing the operating parameters of cooling tower heat replenishment.With regard to the reverse operation of cooling towers and their heat and mass transfer mechanisms, Zhang et al. (2012) developed a coupled heat and mass transfer analytical model and the corresponding finite-difference equations for a counterflow reversible cooling tower, and concluded that the model could provide a theoretical basis for design and performance evaluation. Tan and Deng (2002) operated a standard cooling tower in reverse mode in a subtropical region to extract heat from ambient air and proposed a method for calculating the heat and mass transfer characteristics of a reversibly used cooling tower. Their results showed that the method could be effectively applied to system performance evaluation. Li et al. (2011) investigated a heat pump system using a cooling tower in reverse operation and compared it with an air-source heat pump system, showing that the former exhibited higher operating efficiency under certain conditions.In terms of hybrid heat replenishment systems, Geng (2022) developed an energy tower-ground-source heat pump hybrid heat replenishment system, analyzed the effects of meteorological and soil parameters on heat replenishment characteristics and operating economics, and optimized the operating periods of the system. Shao et al. (2019) proposed using a cooling tower to assist GSHP heat replenishment in summer, with the cooling tower activated when the wet-bulb temperature exceeded 20 °C. Their results showed that the winter water temperature in the buried pipe loop could be maintained at a relatively high level, thereby alleviating the problem of excessively low winter water temperature in heating-only GSHP systems. Overall, previous studies have demonstrated the feasibility of cooling tower-assisted heat replenishment from the perspectives of heat replenishment capacity, reverse-operation heat and mass transfer mechanisms, and the operating performance of hybrid systems. However, most of these studies have focused on equipment performance analysis, local operating conditions, or specific case studies. Systematic investigations into the long-term operational performance, control strategy optimization, and the relationship between underground thermal balance recovery and system energy consumption for hybrid systems in heating-only residential buildings in cold regions remain limited.

Based on the above analysis, this study takes a heating-only residential building in Weifang as the research object and proposes a hybrid system in which a cooling tower is used for cross-seasonal heat replenishment during the non-heating period to address the continuous decline in underground soil temperature and the deterioration of system performance during the long-term operation of a borehole GSHP system. Using the TRNSYS simulation platform, models of both the heating-only GSHP system and the cooling tower-assisted hybrid GSHP system were established to analyze the long-term variations in soil temperature, borehole outlet water temperature, unit COP, and total system energy consumption. On this basis, two operating strategies, namely time-based control and wet-bulb temperature difference control, were further introduced to compare their effects on underground thermal balance recovery and system energy consumption. In addition, an economic analysis of the hybrid system was conducted based on its operating cost. The aim of this work is to provide a reference for the engineering application and operational optimization of heating-only GSHP systems in cold regions.

2. Building Load Analysis

2.1. Building Parameters

A six-story urban residential community located in Fangzi District, Weifang City, with a total developed area of 7128 m², was selected as the research object. A three-dimensional model of the building was created using SketchUp software, as shown in Figure 1. The building envelope and its corresponding heat transfer coefficients are listed in Table 1 (Ministry of Housing and Urban-Rural Development of the People's Republic of China 2016).

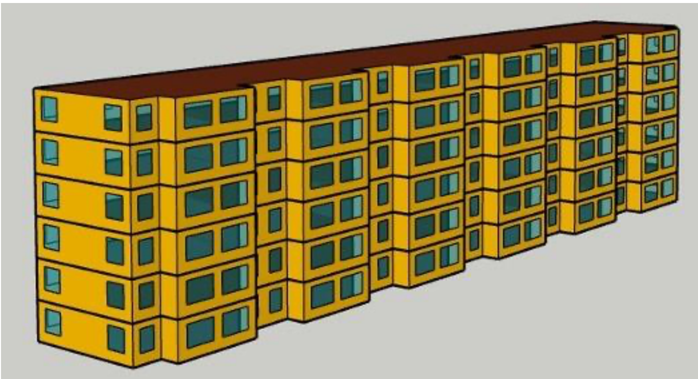


Figure 1. Residential building model.

Table 1. Thermal parameters of the residential building envelope.

Number	Building envelope components	Thermal transmittance /[W/(m²·°C)]
1	Exterior wall	0.215
2	Exterior window	1.69
3	Exterior door	0.743
4	Roof	0.25

2.2. Outdoor Meteorological Parameters

In accordance with the Design Standard for Energy Efficiency of Public Buildings, the indoor design temperatures were set at 20 °C for winter and 26 °C for summer. The residential building is located in Weifang City, Shandong Province, at 36.41 °N and 118.10 °E, and the region is classified as a cold climate zone. The meteorological data of Weifang were obtained and imported into TRNSYS (Zhang et al. 2023). The hourly dry-bulb and wet-bulb temperatures of the region are presented in Figure 2.

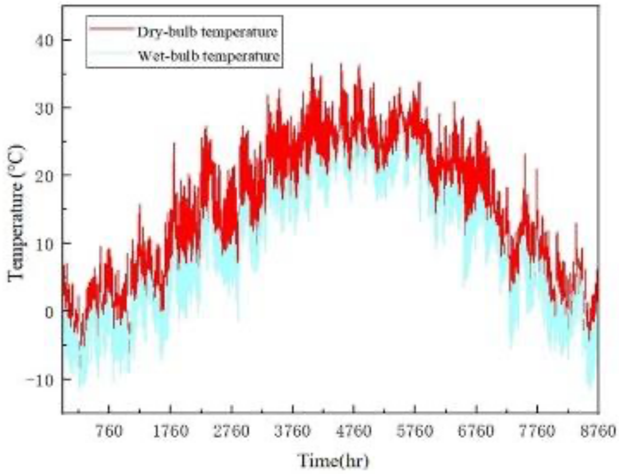


Figure 2. Annual hourly distributions of outdoor dry-bulb and wet-bulb temperatures.

2.3. Building the Load Mode

The simplified 3D model of the building and the meteorological parameters for the Weifang region were imported into TRNSYS software (Zhang et al. 2018). A simulation model for calculating the building load was subsequently established, as illustrated in Figure 3.

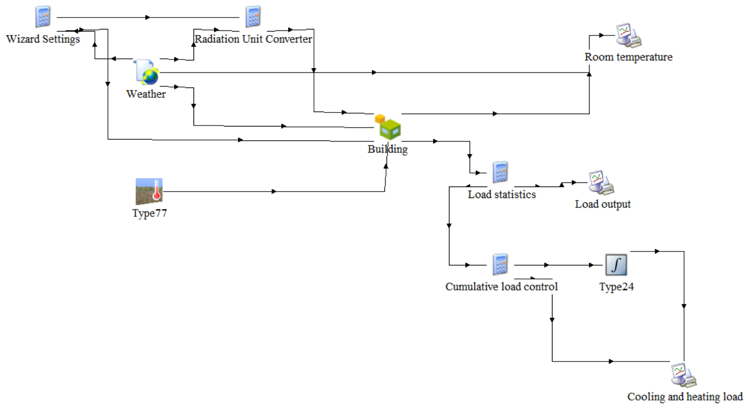


Figure 3. Building the load simulation model.

In the simulation interface, the simulation period was set to the heating season with a time step of 1 h. Here, 0 h corresponds to 00:00 on 15 November, and 2904 h corresponds to 24:00 on 15 March of the following year. Through hourly dynamic simulation, the hourly heating load of the residential building during the heating season was obtained, as shown in Figure 4. The maximum heating load of the building was 291.47 kW.

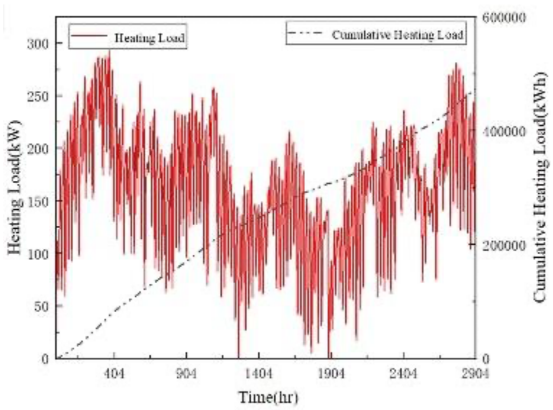


Figure 4. Annual hourly heating load and total load of the building.

3. CONSTRUCTION OF THE SYSTEM SIMULATION MODEL

3.1. MATHEMATICAL MODELS

3.1.1. GROUND SOURCE HEAT PUMP UNIT MODEL

The performance analysis of the GSHP system is based on the following simplified assumptions: interactions among key components, such as the compressor, expansion device, and heat exchangers, are neglected, and heat losses in the pipelines are assumed to be negligible (Yang, Yang and Lü 2013).

According to the principle of energy conservation:

$$Q_{out} = m \cdot C_p(T_{in} - T_{out}) \tag{1}$$

Under the heating mode, the COP is defined as follows:

$$COP = \frac{Q_{out}}{P} = \frac{Q_{out}}{Q_{out} - Q} = \eta_r \cdot \frac{T_{in}}{T_{in} - T_{out}} \tag{2}$$

Where Q_{out} is the heating capacity of the heat pump unit, W; m is the mass flow rate of the terminal circulating water, kg/s; C_p is the specific heat capacity of the terminal circulating water, J/(kg·K); T_{in}, T_{out} are the inlet and outlet water temperatures of the heat pump unit, respectively, °C; P is the power consumption (work input) of the compressor under heating mode, W; Q is the heat absorbed by the ground heat exchanger from the soil, W; and η_r is the overall efficiency coefficient representing the combined efficiency of the heat pump components.

3.1.2. MATHEMATICAL MODEL OF THE GROUND HEAT EXCHANGER

The ground heat exchanger (GHE) module employed is established around the core duct ground heat storage (DST) model, which is used to describe the heat exchange between the soil and the GHE. This model was first proposed by the Swedish professor Hellström (1991). The GHE uses a vertical cylindrical heat source physical model symmetric about its centre, with the assumption that boreholes are uniformly arranged around a cylindrical heat storage region.

The mean fluid temperature within the GHE is given as follows:

$$T_{f,i} = T_{b,i} - \frac{Q_i R_b}{L} - \frac{1}{K_s L}\sum_{i=1}^{n}\sum_{j=1}^{i} Q_j[G(F_0 t_{n+1} - t_i, P) - (F_0 t_n - t_i, P)] \tag{3}$$

According to the principle of energy conservation,

$$Q_i = m_p C_p(T_{po} - T_{pi}) \tag{4}$$

The outlet fluid temperature of the ground heat exchanger is given as follows:

$$T_{po} = Q_n/2m_p C_p \tag{5}$$

Where Q_i is the heat absorbed (or released) by the buried coil in the soil at time i, W; C_p is the specific heat capacity of the heat transfer fluid, kJ/(kg·K); m is the mass flow rate of the heat transfer fluid, kg/s; T_{pi} , T_{po} are the inlet and outlet fluid temperatures of the ground-coupled pipe, respectively, °C; $T_{f,i}$ is the average temperature of the fluid in the ground-coupled pipe at time step i, °C; is the initial soil temperature at time step i, °C; R_b is the borehole thermal resistance, (m·K)/W; L is the borehole depth, m; K_s is the thermal conductivity of the soil, W/(m·K); G is the cylindrical heat source integral; p is the ratio of the radius at the calculation point to the borehole radius; and F_0 is the Fourier number.

3.1.3. COOLING TOWER AUXILIARY HEATING MODEL

When the cooling tower operates in auxiliary heating mode, both heat transfer and mass transfer processes occur. To facilitate calculation, the model is based on the following analytical conditions (Xu 1999):

1. The ratio of the thermal diffusion coefficient to the mass diffusion coefficient is 1.
2. The circulating water surface is saturated air.

3. The water-side thermal resistance is negligible.
4. The heat and mass transfer within the cooling tower is steady-state and occurs only along the flow direction.

To address the soil thermal imbalance in heating-only GSHP systems during long-term operation, this study proposes a composite GSHP–cooling tower system for cross-seasonal soil thermal recharge. Based on an actual residential building, a simulation model is established to evaluate the effects of different control thresholds on soil temperature recovery, heat pump performance improvement, and long-term operational stability, thereby providing theoretical support for the retrofit and optimization of heating-only GSHP systems in existing residential buildings.

Heat exchange occurs between water and air in the cooling tower. The formula for calculating the heat transfer rate is as follows:

$$Q = h_m \cdot A \cdot \left(h_{a,in} - h_{sat,w,in}\right) \tag{6}$$

Where h_m is the mass transfer coefficient, kg/(m²·s); A is the effective contact area between air and water, m2; $h_{a,in}$ is the enthalpy of the inlet air, J/kg; and $h_{sat,w,in}$ is the enthalpy of the saturated air at the water film surface corresponding to the inlet water temperature, J/kg.

According to the energy balance equation,

$$m_w \cdot c_w\left(T_{w,out} - T_{w,in}\right) = m_a \cdot \left(h_{a,out} - h_{a,in}\right) \tag{7}$$

Where m_w, m_a are the mass flow rates of water and air, respectively, kg/s; $T_{w,in}$, $T_{w,out}$ are the inlet and outlet water temperatures, respectively, °C; and $h_{a,in}$, $h_{a,out}$ are the inlet and outlet air enthalpies, respectively, J/kg.

According to the mass conservation equation,

$$m_a w_a = h_m \cdot A(w_w - w_a) \tag{8}$$

Where w_w is the change in the equivalent specific humidity at the water surface, kg/kg, and w_a is the change in the air specific humidity, kg/kg.

3.2. System Equipment Selection

In accordance with the requirements of GB 50189-2015, Design Standard for Energy Efficiency of Public Buildings, and the actual usage needs of the occupants, the design parameters under the heating condition are as follows (Xu et al. 2018):

1. The inlet and outlet water temperatures of the condenser are set at 40 °C and 45 °C, respectively.
2. Under the cooling condition, the inlet and outlet water temperatures of the evaporator are set at 12 °C and 7 °C, respectively.
3. The design parameters of the heat pump unit are determined based on the required heating or cooling load and the environmental conditions.

Accordingly, a single GSHP unit was selected for standalone operation. The system was sized with a safety factor of 1.15 relative to the maximum heating load. A single U-tube ground heat exchanger made of high-density polyethylene (HDPE) pipe was adopted (China Academy of Building Research 2009; Ministry of Construction of the People's Republic of China 2006). The inner and outer diameters of the U-tube are 26 mm and 32 mm, respectively, and the borehole spacing is 5 m. Field measurements indicate that the average initial soil temperature is 16 °C, and the design flow velocity inside the pipe is 0.6 m/s. Based on the building load, a total of 75 boreholes were designed for the heating-only ground-source heat pump system. The calculation process is presented below (Li et al. 2025), and the equipment specifications are listed in Table 2.

$$n = \frac{Q(1 - COP)}{qh} \tag{9}$$

Where *n* is the number of boreholes for ground heat exchange in the system; Q is the building heating load, W; COP is the coefficient of performance of the GSHP unit; h is the borehole depth, m; and q is the heat exchange capacity per metre during winter, W/m.

Table 2. Equipment selection of the ground-source heat pump system.

System component	Equipment parameters
Ground-source heat pump unit	Rated heating capacity: 320.6 kW; condenser outlet water temperature: 45 ℃; heating supply/return water temperature difference: 5 ℃; evaporator inlet temperature: 10 ℃; source-side supply/return water temperature difference: 5 ℃.
Ground-side circulating pump	Flow rate: 61.71 m³/h; pump power: 3.96 kW; supply/return water temperature difference: 5 ℃.
Load-side circulating pump	Flow rate: 57.69 m³/h; pump power: 3.69 kW; supply/return water temperature difference: 5 ℃.
Cooling tower	The design inlet water flow rate was 120 m³/h, and the air flow rate was 180,000 m³/h.

For the cooling tower-assisted GSHP hybrid system, the ground-source heat pump independently supplies the maximum building heating load in winter, and the number of boreholes used in the ground heat exchanger is the same as that in the heating-only GSHP system. Based on the cumulative building heating load and the rated heating COP of the heat pump unit, the cumulative heat extraction from the ground heat exchanger can be calculated. Assuming a heat loss rate of 20% during the transitional season, the required amount of heat replenishment to the soil can then be determined. The calculation formula is given as follows:

$$Q_t = \sum Q_r (1-\frac{1}{COP})(1+20\%) \tag{10}$$

Where Q_t is the compensation heat for the soil (kW);COP is the rated coefficient of performance of the unit; $\sum Q_r$ is the cumulative heating load of the building (kW).

Considering that heat storage should be carried out when the outdoor air temperature is relatively high, it was assumed that the cooling tower operated continuously during the heat storage period. Based on the total required heat compensation, and taking into account system operation and heat transfer losses, an additional design factor of 1.2 was adopted, resulting in a design heat replenishment capacity of 278.48 kW for the cooling tower during the heat storage period. According to the measured operating conditions during the transitional season in Weifang, the average temperature rise of the circulating water through the cooling tower was taken as 2 °C. Under these conditions, the required circulating water flow rate was calculated to be 120 m³/h, using the following formula:

$$G = \frac{P_b}{c \cdot \rho \cdot \Delta t} \times 3.6 \tag{11}$$

Where G is inlet water flow rate of the cooling tower, m³/h; P_b is average heat replenishment of the cooling tower, kW;c is specific heat capacity of water, kJ/(kg·℃);ρ is density of water, kg/m³;Δt is temperature difference between the inlet and outlet of the cooling tower.

According to reference (Wen, Liang and Zhang 2011), when the water-to-air ratio is 0.56 (generally defined as the ratio of the mass flow rate of water to the mass flow rate of air), the auxiliary heat supply of the cooling tower reaches an optimal state, and the air flow rate of the cooling tower can be calculated as 1.8×10^5m/h. The selected equipment specifications are listed in Table 2.

3.3. Construction of the Simulation Model

TRNSYS includes several components, such as Simulation Studio, TRNBuild, TRNEdit, and TRNOPT, and is widely used by researchers worldwide. Due to its convenient modeling process, high computational efficiency, and rich module resources, TRNSYS is extensively employed in simulation studies of complex energy systems. In this study, TRNSYS 18 was selected as the simulation tool because of its strength in modular analysis. The modules used in this study are listed in Table 3.

Table 3. Main modules of the system simulation model and their corresponding type numbers.

Module	Description
Type225	Heat pump unit
Type15	Weather data processor
Type682	Ideal terminal unit
Type557	Borehole heat exchanger
Type-9e	Load data reader
Type65	Online plotter
Type24	Integrator
Type162	Cooling tower

Module	Description
Type11d	Diverter valve
Type11f	Mixer valve
Type2	Differential controller
Equation	Equation block

3.3.1. Model Construction of the Heating-Only Ground-Source Heat Pump System

Based on the above system module configuration and the relevant parameter settings, a simulation model of the heating-only ground-source heat pump system was established on the TRNSYS platform, as shown in Figure 5. In this model, data are transferred among the submodules through state variables such as temperature, flow rate, and energy, while start-stop control and operating mode switching are achieved through control signals, enabling the model to reflect the dynamic operating characteristics and energy consumption of the system during the heating period.

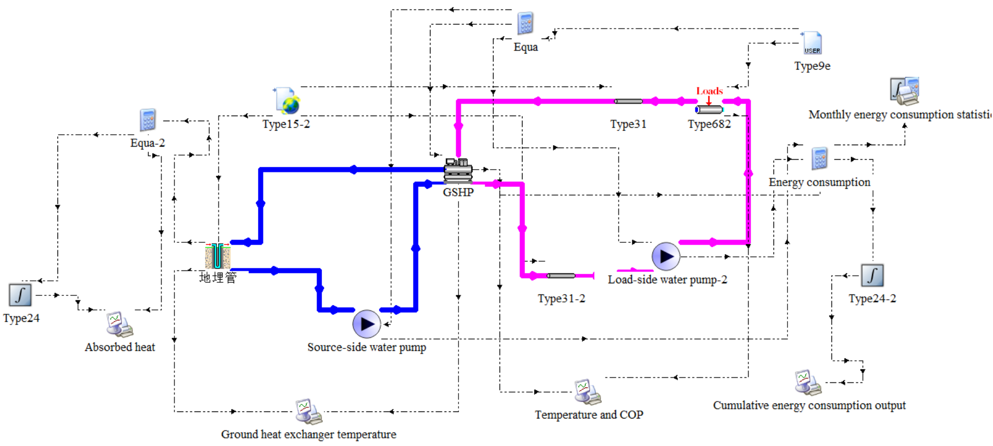


Figure 5. TRNSYS simulation model of the heating-only GSHP system.

Because the system is designed for heating only, it operates exclusively during the heating season. During this period, the circulating water temperature in the ground heat exchangers remains relatively low and continuously extracts heat from the surrounding soil to meet the heating demand on the load side. As a result, the soil temperature gradually decreases over the simulation period. As shown in Figure 6, the average soil temperature decreased from the initial value of 16.00 °C to 13.72 °C after the first year and further declined to 9.74 °C after four years of operation, indicating a substantial reduction relative to the initial condition. Since the system does not reject heat back into the ground, the inlet and outlet water temperatures of the ground heat exchangers decrease year by year as the soil temperature declines, which in turn leads to a reduction in the coefficient of performance (COP) of the GSHP unit (Li et al. 2024). From the fourth year onward, the minimum winter inlet water temperature of the ground heat exchangers falls below the lower limit of 4 °C specified in the technical code for ground-source heat pump systems. Continued operation under these conditions may cause freezing in the ground loops, thereby threatening the normal operation of the system.

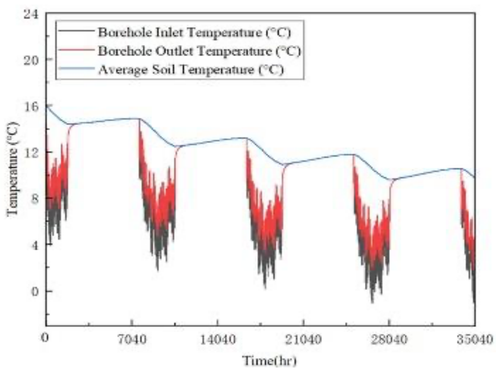
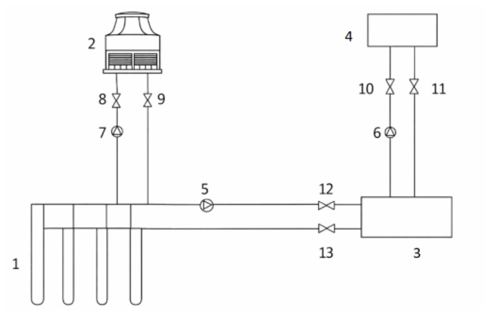


Figure 6. Variations in soil temperature and the inlet/outlet water temperatures during winter over a 10-year simulation.

3.3.2. Construction of the Simulation Model for the Ground-Source Heat Pump–Cooling Tower Hybrid System

During the long-term operation of a heating-only ground-source heat pump system, continuous heat extraction from the soil leads to cumulative cold accumulation around the boreholes, causing underground thermal imbalance and reducing the overall operating efficiency of the system. Therefore, replenishing heat to the soil is considered an effective measure to address this problem (Liu et al. 2019). The hybrid thermal storage system mainly consists of ground heat exchangers, a ground-source heat pump unit, water pumps, a cooling tower, terminal units, and other auxiliary equipment. In winter, the ground-source heat pump operates independently to provide heating. In summer and during the transitional seasons, the cooling tower is operated during specific periods to transfer heat from the outdoor air to the soil, thereby mitigating soil cold accumulation, improving soil thermal conditions, maintaining the normal operation of the heat pump unit, and achieving cross-seasonal heat storage (Tang et al. 2024). The schematic diagram of the hybrid system is shown in Figure 7.



1—Ground heat exchanger; 2—Cooling tower; 3—Ground-source heat pump unit; 4—Building load side; 5—Ground-side water pump; 6—Load-side water pump; 7—Heat replenishment water pump; 8, 9, 10, 11, 12, and 13—Valves.

Figure 7. Schematic diagram of the hybrid ground-source heat pump and cooling tower system.

The system mainly operates in two modes: the conventional heating mode in winter and the heat replenishment mode during the transitional season. Switching between these two modes is achieved through valve control, and the specific operating processes are described as follows.

3.3.3.2. Conventional Heating Mode

In the conventional heating mode, the system operates during winter. In this mode, water pumps No. 5 and No. 6 are activated, and valves No. 10, 11, 12, and 13 are opened, while all other valves remain closed. On the ground-source side, the circulating water first flows through the ground heat exchanger, where it exchanges heat with the surrounding soil. After absorbing heat from the ground, it returns to the ground-source heat pump unit and serves as the heat source for the evaporator. On the load side, the circulating water is heated by the heat pump unit and then delivered to the building load side to meet the heating demand. Under this mode, the system continuously extracts heat from the underground soil through the ground heat exchanger, resulting in a gradual reduction in the heat stored in the soil around the boreholes.

3.3.3.3. Transitional Season Heat Replenishment Mode

During the transitional season heat replenishment mode, the ground-source heat pump unit is shut down. Water pump No. 7 (the heat replenishment pump) is activated, and valves No. 8 and No. 9 are opened, while all other valves remain closed. In this mode, the circulating water is first driven by the heat replenishment pump through the cooling tower, where it exchanges heat with the outdoor air and absorbs heat from it. After its temperature rises, the heated water enters the ground heat exchanger loop. It then flows through the borehole heat exchanger and transfers heat to the surrounding soil through the pipe wall, thereby injecting the absorbed air-side heat into the underground ground mass.

The TRNSYS simulation model of the ground-source heat pump-cooling tower hybrid system is shown in Figure 8.

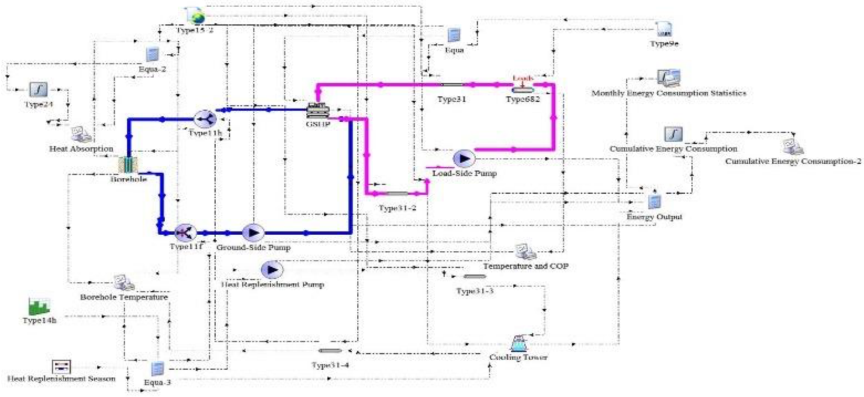


Figure 8. TRNSYS simulation model of the hybrid ground-source heat pump and cooling tower system.

4. Control Strategy Analysis of the Hybrid System

This paper employs a time and temperature-difference limit control strategy to manage the cooling tower operation in the hybrid system. The ground-source heat pump system alone meets the building heating load in winter, while in summer and transition seasons, the cooling tower is switched on/off based on predefined control setpoints to store heat from the air side and transfer it to the ground.

4.1. Operation Analysis under Time Control Strategy

According to the meteorological conditions in Weifang, the outdoor air temperature and humidity are relatively high during summer and the transitional seasons, providing favorable conditions for air-side heat replenishment. Accordingly, a time-based control strategy was adopted, under which the cooling tower is activated during periods of relatively high outdoor temperature in the non-heating season to absorb heat from the ambient air and transfer it to the ground through the ground heat exchanger, thereby improving underground thermal conditions.

On this basis, an hourly dynamic simulation of the hybrid system was carried out over the entire year. The output parameters included soil temperature, outlet water temperature of the ground heat exchanger, COP of the heat pump unit during the heating season, cumulative heat storage of the cooling tower, cumulative heat extraction of the ground heat exchanger, and annual system energy consumption.

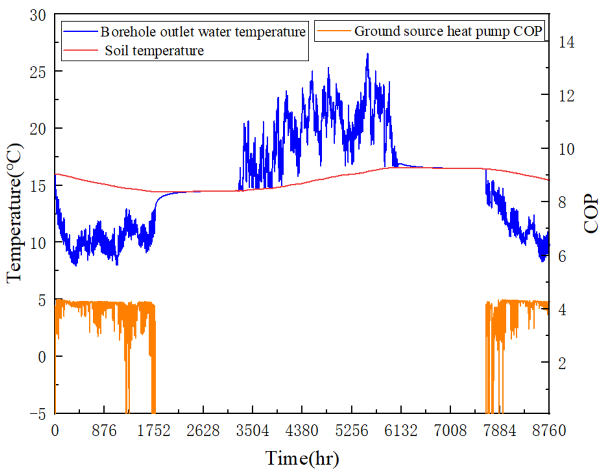


Figure 9. Variations in temperature and COP for the hybrid system over a one year simulation.

As shown in Figure 9, after one year of operation of the cooling tower-assisted ground-source heat pump hybrid system, the average soil temperature decreased from the initial value of 16.00 °C to 15.45 °C, representing a reduction of 0.55 °C, while the outlet water temperature of the ground heat exchanger decreased to 9.68 °C. During the heating season, the ground-source heat pump continuously extracts heat from the soil, causing the soil temperature to decrease gradually and the outlet water temperature of the ground heat exchanger to remain at a relatively low level. During the non-heating season, once the cooling tower is activated, it absorbs heat from the ambient air and transfers it to the ground, resulting in a recovery of soil temperature and a significant increase in the outlet water temperature of the ground heat exchanger. This indicates that cooling tower-assisted heat replenishment can improve underground thermal conditions to a certain extent. At the beginning of the following heating season, both the average soil temperature and the outlet water temperature of the ground heat exchanger decrease again. However, the overall variations remain relatively stable, suggesting that, with the aid of cooling tower heat replenishment, the underground thermal conditions do not deteriorate excessively after one year of system operation. From the perspective of heat pump performance, the COP of the unit during the heating season remains at approximately 4.0, indicating that the unit still maintains good heating performance under these operating conditions.

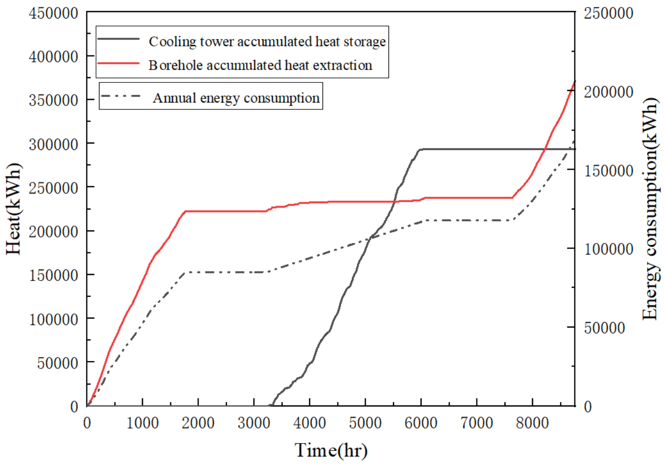


Figure 10. Heat storage of the cooling tower, heat extraction of the ground heat exchanger, and annual energy consumption of the hybrid system over a one-year simulation.

As shown in Figure 10, in terms of thermal balance, after one year of system operation, the cumulative heat extracted from the soil by the ground heat exchanger was 371,424.08 kWh, while the cumulative heat stored into the soil via the cooling tower was 293,580.21 kWh. The calculated soil thermal imbalance ratio is approximately 21% (Zhang and Wei 2012). From the perspective of energy consumption, under the time control strategy, the cumulative energy consumption of the system in the first year was 169,122.3 kWh. The energy consumption in the tenth year increased by 1,215.7 kWh compared to the first year, and the total cumulative energy consumption over the ten-year period was 1.70 GWh. Overall, the variation in system energy consumption during the ten-year operation period is relatively small, indicating that the system operates at a consistently stable level.

$$\varepsilon = \frac{Q_d - Q_l}{Q_d} \tag{12}$$

Where ε is the thermal imbalance ratio, %; Q_d is the heat extracted from the soil by the ground heat exchanger, kWh; and Q_l is the heat absorbed by the cooling tower, kWh.

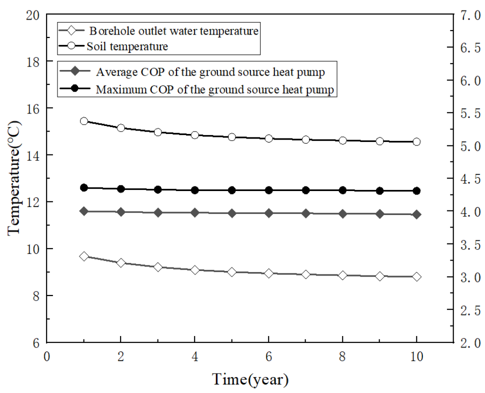


Figure 11. Variations in the temperature and COP of the hybrid system over a ten-year simulation.

From a long-term operational perspective, the system performance indicators show a year-by-year decline, while the rate of decline gradually decreases over time. As the operating period extends, the decreasing trends in both soil temperature and the outlet water temperature of the ground heat exchanger gradually level off. The simulation results indicate that, by the tenth year of operation, the cumulative reduction in soil temperature reaches 1.44 °C, and the outlet water temperature of the ground heat exchanger decreases to 8.81 °C. The declines in both the maximum COP and the average COP of the heat pump unit also become smaller year by year. By the tenth year, the maximum COP decreases by 0.06 compared with that in the first year, while the average COP decreases by 0.05. These results indicate that cross-seasonal heat replenishment by the cooling tower can help maintain soil thermal balance to a certain extent, thereby contributing to the long-term stable operation of the ground-source heat pump system.

4.2. Operational Analysis under Temperature Difference Threshold Control

Under the wet-bulb temperature difference threshold control strategy, four threshold values of 1 °C, 3 °C, 5 °C, and 7 °C are set, corresponding to operating strategies A1, A2, A3, and A4, respectively. The control logic is as follows: when the temperature difference between the outdoor wet-bulb temperature T_{wb} and the outlet water temperature of the ground heat exchanger T_{out} , defined as $\Delta T = T_{wb} - T_{out}$, is greater than the preset threshold, the cooling tower is turned on (Gu, Chen and Hu 2017). In this case, the circulating water absorbs heat from the ambient air and transfers it into the ground to compensate for the soil heat deficiency and restore soil temperature. When ΔT falls below the threshold, the cooling tower is turned off.

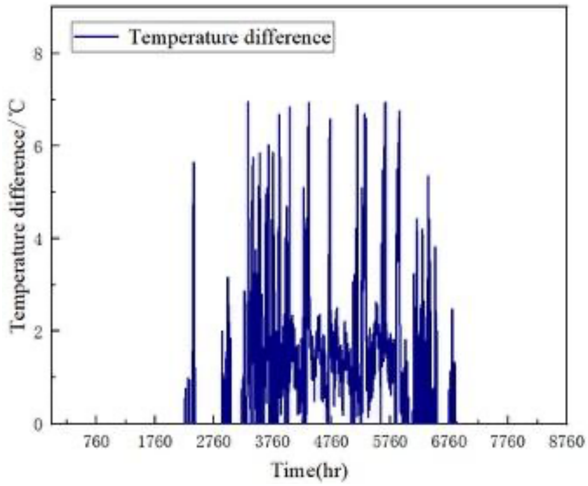


Figure 12. The temperature difference between the outdoor wet-bulb temperature and the outlet water temperature of the ground heat exchanger.

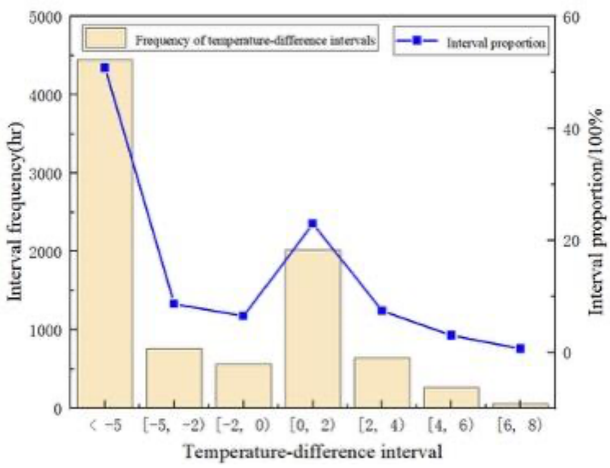


Figure 13. Frequency distribution of ΔT between the outdoor wet-bulb temperature and the outlet water temperature of the ground heat exchanger.

Figures 12 and 13 show the hourly difference between the outdoor wet-bulb temperature and the outlet water temperature of the ground heat exchanger over the year, together with its frequency distribution. The statistical results indicate that negative temperature differences occur for approximately 65.94% of the year, meaning that the outdoor wet-bulb temperature is lower than the water temperature and that the air side therefore cannot provide favorable conditions for reverse heat extraction. Among the periods with positive temperature differences, during which heat extraction is feasible, the magnitude of ΔT is generally small, with the maximum value remaining below 8 °C. Specifically, the highest cumulative time proportion occurs when ΔT is in the range of 0–2 °C, reaching 23.01%; the corresponding proportions for the ranges of 2–4 °C, 4–6 °C, and 6–8 °C are 7.40%, 3.02%, and 0.63%, respectively.

Based on these statistical results, this study selected 1 °C, 3 °C, 5 °C, and 7 °C as the wet-bulb temperature difference thresholds for the long-term simulation of the control strategy. These threshold values cover the main distribution range of the local wet-bulb temperature difference and make it possible to evaluate variations in the operating duration and heat replenishment capacity of the cooling tower under different activation conditions. They also provide a basis for further analysis of soil temperature recovery and long-term system energy consumption under different operating scenarios.

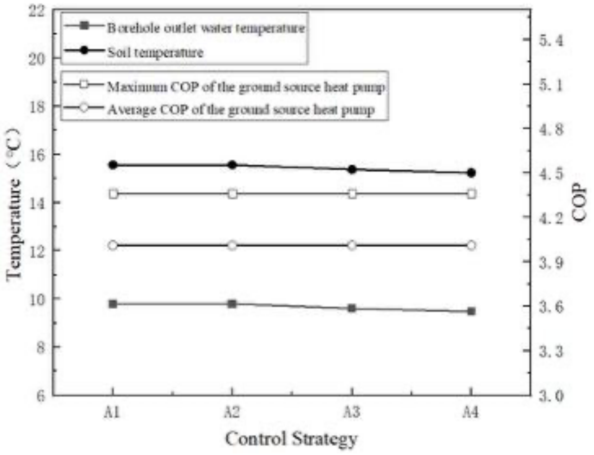


Figure 14. Variations in temperature and COP of the hybrid system after one year of simulation.

As shown in Figure 14, after one year of operation of the hybrid system, differences in soil temperature, outlet water temperature of the ground heat exchanger, and heat pump COP were observed under different wet-bulb temperature difference control strategies (A1–A4). As the control strategy changed from A1 to A4, the outlet water temperature of the ground heat exchanger decreased from 9.79 °C to 9.47 °C, corresponding to a decrease of 0.32 °C, while the soil temperature decreased from 15.56 °C to 15.24 °C, also by 0.32 °C. This indicates that, as the activation threshold increases, the amount of heat replenishment during the non-heating season decreases, leading to a corresponding deterioration in the heat exchange conditions of the ground heat exchanger. In terms of unit performance, the maximum COP under each operating condition was 4.36, and the average COP was 4.01, showing little variation. This suggests that, within the considered control range, the system was able to maintain good heating performance.

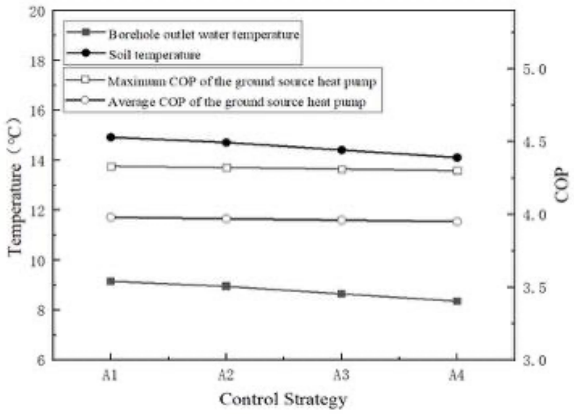


Figure 15. Variations in temperature and COP of the hybrid system after ten year of simulation.

As shown in Figure 15, the lower the preset temperature difference threshold, the greater the degree of soil temperature recovery after ten years of system operation. The simulation results showed that, after ten years of operation, the soil temperatures corresponding to strategies A1, A2, A3, and A4 were 14.92 °C, 14.71 °C, 14.41 °C, and 14.11 °C, respectively. Among these strategies, A1 resulted in the smallest decrease in soil temperature, which was 1.08 ℃ below the initial value, whereas A4 produced the largest decrease, with a total reduction of 1.89 °C. When the activation temperature difference threshold for ground heat exchanger heat replenishment was set to a higher value, the operating duration of the cooling tower became shorter, leading to a more pronounced decline in soil temperature. The outlet water temperature of the ground heat exchanger showed the same trend as the soil temperature. Under strategy A4, after ten years of operation, the soil temperature decreased by 1.89 °C, the outlet water temperature of the ground heat exchanger dropped to 8.36 °C, and the maximum COP and average COP of the heat pump unit decreased by 0.05 and 0.06, respectively. These reductions were relatively small, indicating that the system was still able to maintain stable heating performance over the ten-year operating period.

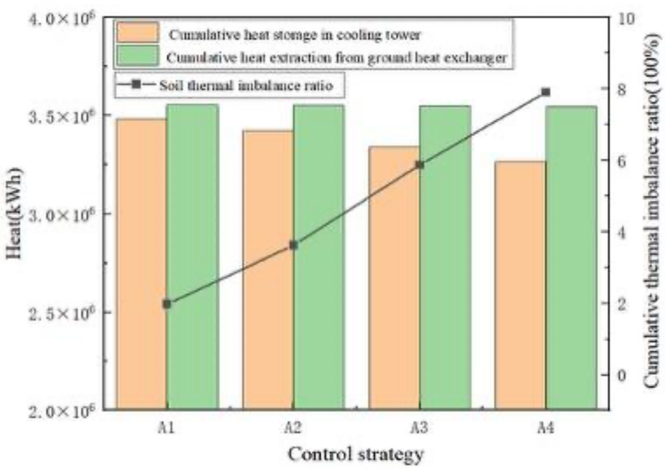


Figure 16. Ten-year simulation results of cooling tower heat storage, ground heat exchanger heat extraction, and soil thermal imbalance ratio for the hybrid system.

As shown in Figure 16, as the control strategy gradually changes from A1 to A4, the cumulative heat storage of the cooling tower continuously decreases, while the cumulative heat extraction of the ground heat exchanger exhibits little variation, resulting in a gradual increase in the soil thermal imbalance ratio. The cumulative heat storage of the cooling tower decreases by 6.27% from A1 to A4. Correspondingly, the soil thermal imbalance ratio increases from 1.97% under A1 to 3.62% under A2, 5.87% under A3, and 7.91% under A4. These results indicate that the higher the set wet-bulb temperature difference threshold, the fewer the periods during which the cooling tower meets the activation conditions, the shorter its operating time, and the less heat it extracts from the air side, thereby leading to a reduction in cumulative heat storage.

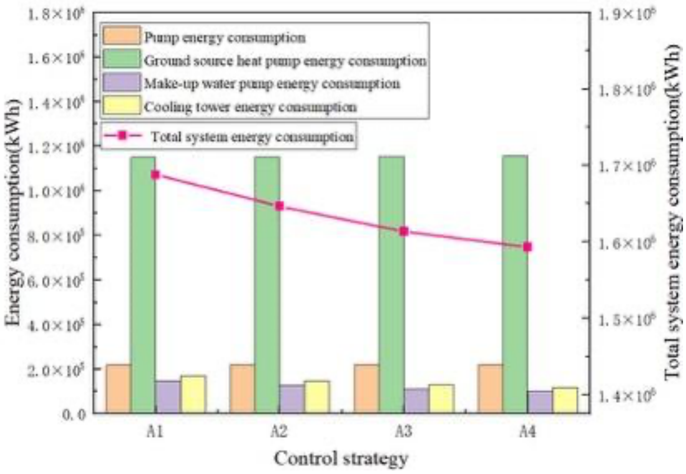
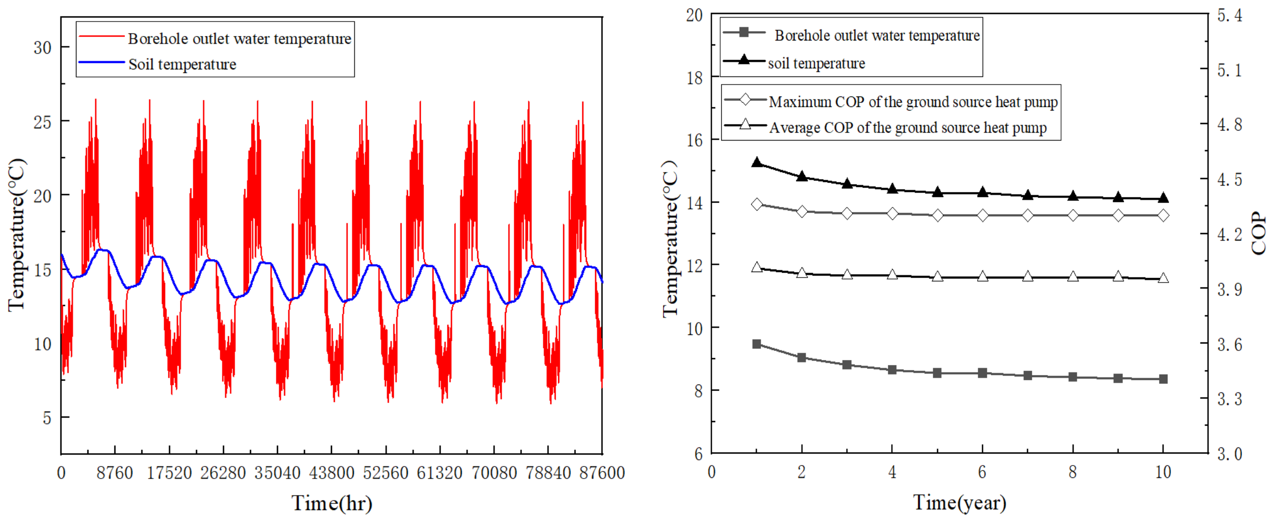


Figure 17. Ten-year cumulative energy consumption comparison of the hybrid system.

As shown in Figure 17, after ten years of operation, the cumulative energy consumption values for A1, A2, A3, and A4 are 1.68 GWh, 1.64 GWh, 1.61 GWh, and 1.59 GWh, respectively, with strategy A4 exhibiting the lowest cumulative energy consumption. Compared with A1, A2, and A3, the energy consumption of A4 is reduced by approximately 5.3%, 3.0%, and 1.2%, respectively. Thus, strategy A1 is more favorable for increasing soil temperature levels, but it incurs higher energy consumption. Under strategy A4, the cumulative heat storage of the cooling tower is smaller, and the degree of soil temperature elevation is relatively weaker, yet the cumulative energy consumption of the system is the lowest. If soil temperature recovery is used as the sole evaluation criterion, A1 outperforms the other strategies. However, when comprehensively considering soil temperature maintenance, thermal imbalance ratio, and cumulative system energy consumption, A4 achieves the lowest energy consumption while ensuring long-term stable system operation. Therefore, this study identifies A4 as the control strategy with the optimal overall performance.



(**a**) Variation of borehole outlet water temperature and average soil temperature

(**b**) Variation of the average winter COP

Figure 18. Soil temperature variation and energy consumption change of the hybrid system over a 10-year simulation.

As shown in Figure 18, under strategy A4, both the average soil temperature and the outlet water temperature of the ground heat exchanger remained relatively stable over the ten-year operating period. The average soil temperature decreased only slightly with increasing operating years, without showing obvious continuous deterioration. This indicates that, under strategy A4, cooling tower heat replenishment during the transitional seasons can partially compensate for the heat extracted from the ground during the heating season, thereby mitigating the decline in soil temperature to a certain extent. In terms of heat pump performance, both the maximum COP and the average COP varied only slightly over the operating years. Taking the average COP as an example, it decreased by only 0.05 after ten years compared with that in the first year and remained at approximately 3.95. Considering the long-term trends of soil temperature, outlet water temperature of the ground heat exchanger, and COP, strategy A4 maintained relatively stable underground operating conditions while achieving low long-term energy consumption. Therefore, under the conditions considered in this study, strategy A4 showed a comparatively better overall balance for the hybrid system.

4.3 Comparative Analysis of the Two Control Strategies

To compare the overall performance of the two control strategies, the optimal wet-bulb temperature difference control strategy (A4) was compared with the time-based control strategy. The variations in soil temperature and the cumulative heating–cooling imbalance ratio after 10 years of operation were analyzed, and the results are presented in the figure.

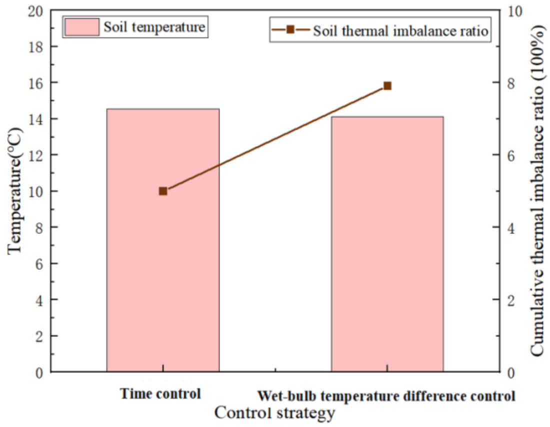


Figure 19. Soil temperature and cumulative heating–cooling imbalance ratio under different control strategies.

As shown in Figure 19, after 10 years of operation, the soil temperature under the time-based control strategy recovered to 14.56 °C, with a cumulative heating–cooling imbalance ratio of 5.00%; under the wet-bulb temperature difference control strategy, the soil temperature was 14.11 °C, and the cumulative heating–cooling imbalance ratio was 7.91%. Compared with the wet-bulb temperature difference control strategy, the time-based control strategy resulted in a 0.45 °C higher soil temperature and a 2.91% lower cumulative heating–cooling imbalance ratio. This indicates that the time-based control strategy provides more sufficient heat injection during the non-heating period and delivers a greater total amount of heat to the ground, thereby leading to better soil thermal recovery.

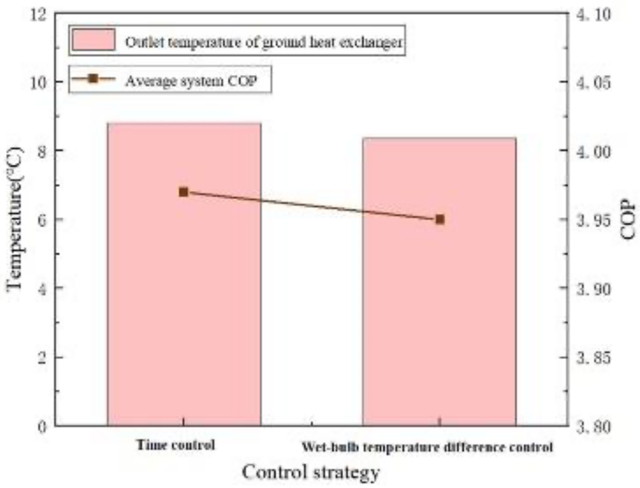


Figure 20. Variation in outlet water temperature of the buried pipe and COP under different control strategies.

As shown in Figure 20, under the time-based control strategy, the outlet water temperature of the buried pipe in the tenth year was 8.81 °C, and the average COP of the system over the 10-year period was 3.97. Under the wet-bulb temperature difference control strategy, the outlet water temperature was 8.36 °C, and the average COP was 3.95. Overall, the differences in the outlet water temperature of the buried pipe and the unit energy efficiency between the two strategies were small. Both strategies were able to ensure a relatively stable heating operation of the heat pump unit over the long term, and no obvious performance deterioration caused by soil cold accumulation was observed.

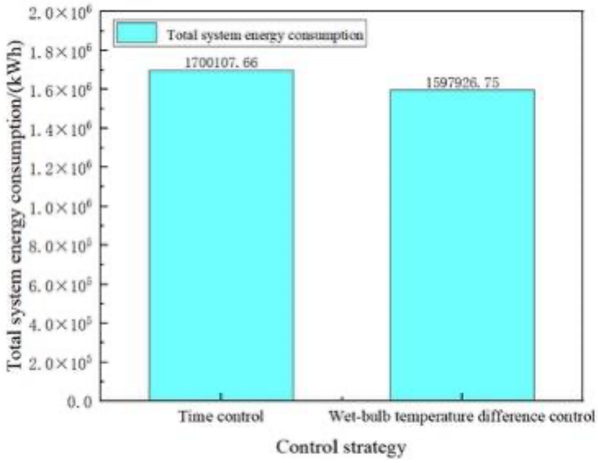


Figure 21. Total system energy consumption under different control strategies.

As shown in Figure 21, there was a clear difference in total system energy consumption between the two control strategies. The 10-year simulation results indicate that the total energy consumption under the time-based control strategy was 1,700,107.66 kWh, whereas that under the wet-bulb temperature difference control strategy was 1,597,926.75 kWh. Although the time-based control strategy performed slightly better in terms of soil temperature maintenance and average COP, its operation within fixed time periods did not take outdoor air conditions into account, resulting in additional energy consumption when the cooling tower operated under conditions with insufficient heat transfer potential. In contrast, the wet-bulb temperature difference control strategy enabled heat extraction during periods of higher temperature and humidity, thereby reducing ineffective energy consumption of the cooling tower and circulating pump, and lowering the total system energy consumption by approximately 102,000 kWh.

Overall, although the wet-bulb temperature difference control strategy was slightly inferior to the time-based control strategy in terms of soil temperature recovery, the soil temperature under both strategies remained above 14 °C after 10 years of operation. Considering both soil temperature maintenance and long-term system energy consumption, the wet-bulb temperature difference control strategy achieved a better balance between maintaining underground thermal equilibrium and reducing system energy use, and is therefore more suitable as the control strategy for cross-seasonal heat storage of the hybrid system under the conditions considered in this study.

5. Comparative Analysis of the Hybrid System and the Heating-Only Ground Source Heat Pump System

From the above analysis, it can be seen that the heating-only ground-source heat pump system and the cooling tower-assisted hybrid ground-source heat pump system exhibit significant differences in long-term operational characteristics. In the heating-only ground-source heat pump system, heat is continuously extracted from the ground during the heating season, while no effective heat replenishment is provided during the non-heating period. As a result, cold accumulation on the ground side becomes increasingly severe, and the soil temperature decreases year by year. As shown in Table 4, after four years of operation, the soil temperature of the heating-only ground-source heat pump system decreased from 13.88 °C to 9.74 °C, indicating a marked deterioration in underground heat exchange conditions, and the system could no longer maintain safe and stable operation thereafter. In contrast, the hybrid system can, to a certain extent, compensate for the heat extracted from the ground during the heating season by injecting heat into the ground through the cooling tower during the non-heating period, thereby slowing the rate of soil temperature decline. As shown in Table 5, under the conditions considered in this study, the soil temperature of the hybrid system remained above 14.11 °C after 10 years of operation, indicating that the system was able to maintain more reasonable underground thermal conditions and operating performance over a longer time scale. These results suggest that, compared with the heating-only system, the hybrid system performs better in improving the underground thermal environment and supporting long-term operation.

Table 4. Calculated soil temperature and operating costs for the heating-only ground-source heat pump system over a normal 4-year heating.

Operation time/a	1	2	3	4
Soil temperature/°C	13.88	12.22	10.81	9.74
Operating cost/(CNY·m⁻²)	13.43	13.64	13.86	14.12

Table 5. Calculated soil temperature and operating costs for the hybrid system over a 10-year heating season.

Operation time/a	1	2	3	4	5	6	7	8	9	10
Soil temperature/°C	15.42	15.11	14.91	14.78	14.68	14.62	14.56	14.52	14.49	14.11
Operating cost/(CNY·m⁻²)	15.21	15.35	15.57	15.63	15.69	15.73	15.81	15.81	15.82	15.82

Note: The electricity price is 0.70 CNY/kWh.

From an economic perspective, Table 5 shows that the operating cost of the hybrid system gradually stabilized with increasing years of operation. Because a cooling tower and a supplementary heat injection circulation loop were added to the original ground-source heat pump system, and the cooling tower needs to be operated for heat replenishment during the transitional season when certain conditions are met, additional electricity consumption and operating costs are inevitably introduced. Although the heat replenishment process increases system energy use, the decline in soil temperature is significantly slowed compared with that before heat replenishment, allowing the ground-source heat pump system to maintain normal operation. The calculated operating cost per unit building area gradually stabilized at approximately 15.82 CNY/m². It should be noted that this study only obtained long-term operating cost data for the hybrid system. Since the heating-only ground-source heat pump system became unable to continue normal operation after four years, the two systems do not provide a basis for direct comparison of operating costs over a unified operating period. Under such circumstances, evaluating system economics solely on the basis of short-term operating cost would not adequately reflect the practical engineering value of the hybrid system in extending the service period through heat replenishment.

Under the design conditions considered in this study, the initial investment, annual operating cost, and equivalent annual cost of the hybrid system were 579,792 CNY, 87,885.6 CNY, and 119,774.5 CNY, respectively. Although the introduction of the cooling tower and the supplementary heat injection pump increased the system investment and operating expenditure, these additional costs led to an improved underground thermal environment and enhanced the long-term operational capability of the system. Since the heating-only ground-source heat pump system became difficult to operate stably after approximately four years, whereas the hybrid system was still able to maintain normal operation over a 10-year period, the additional investment and operating cost of the hybrid system may be regarded, from a life-cycle perspective, as a necessary expenditure for ensuring continuous system operation.

6. CONCLUSIONS

Taking a heating-only residential district in Weifang as the research object, this study investigated the operational performance and control strategies of cross-seasonal heat replenishment using a cooling tower to address the problem of underground cold accumulation during the long-term operation of heating-only ground-source heat pump systems. Based on the simulation results obtained under the climatic conditions, system parameters, and operating modes considered in this study, the following conclusions can be drawn.

1. During the long-term operation of a heating-only ground-source heat pump system, continuous heat extraction from the ground during the heating season, coupled with the lack of effective heat replenishment during the non-heating period, leads to increasingly severe cold accumulation on the ground side and a continuous decline in soil temperature. After four years of operation, the soil temperature decreased from 13.88 °C to 9.74 °C, and the underground heat exchange conditions deteriorated markedly, making it difficult for the system to maintain safe and stable operation thereafter. In contrast, the cooling tower-assisted hybrid ground-source heat pump system can partially compensate for the heat extracted from the ground during the heating season by injecting heat into the ground during the non-heating period, thereby slowing the decline in soil temperature. The results show that the soil temperature of the hybrid system remained above 14 °C after 10 years of operation, indicating that this system can effectively alleviate underground thermal imbalance and maintain a relatively favorable

long-term operating state.

2. Different control strategies exhibited different characteristics in terms of soil temperature recovery and system energy consumption. The time-based control strategy performed slightly better in terms of soil temperature recovery, whereas the wet-bulb temperature difference control strategy A4 resulted in lower total system energy consumption. After 10 years of operation, the total energy consumption under the wet-bulb temperature difference control strategy was approximately 6% lower than that under the time-based control strategy. Although the soil temperature under Strategy A4 was slightly lower than that under the time-based control strategy, both strategies were able to maintain relatively reasonable underground thermal conditions and stable heat pump operation. Therefore, within the parameter range and evaluation criteria adopted in this study, Strategy A4 achieved a comparatively better overall balance between maintaining underground thermal equilibrium and controlling long-term energy consumption.
3. From an economic perspective, the hybrid system required higher initial investment and operating cost because of the addition of the cooling tower and the supplementary heat injection pump. Under the design conditions considered in this study, the initial investment, annual operating cost, and equivalent annual cost of the hybrid system were 579,792 CNY, 87,885.6 CNY, and 119,774.5 CNY, respectively. Although the heat replenishment process introduced additional energy consumption, it significantly slowed the decline in soil temperature compared with the condition before heat replenishment, allowing the system to maintain normal operation, while the operating cost per unit building area gradually stabilized at approximately 15.82 CNY/m². Since the hybrid system was able to maintain relatively reasonable underground thermal conditions and system operation over a 10-year period, the additional investment and operating cost may be regarded as a necessary expenditure for ensuring continuous system operation. It should be noted that the applicability of the proposed control strategy and the corresponding economic conclusions to other climate zones, building types, and system configurations still requires further investigation. Future work may focus on experimental validation or on extending the study to a broader range of climatic conditions and building application scenarios.

AUTHOR CONTRIBUTIONS

Qinhan Guo: Conceptualization; Methodology; Software; Formal analysis; Investigation; Writing - original draft. **Yan Li**: Literature review; Writing-review & editing. **Qianchang Li**: Literature review; Writing -review & editing. **Wenke Zhang**:Supervision; Literature review; Writing-review & editing. **Shanshan Zhang**:Literature review; Writing – review & editing. **Zhaoyi Zhuang**: Literature review; Writing-review & editing. **Jie Liu**:Literature review; Writing – review & editing.

COMPETING INTERESTS

The authors declare that they have no competing interests.

DATA ACCESSIBILITY

The meteorological data, building parameters, soil properties, and key simulation parameters used in this study have been presented in the manuscript. Some engineering background data are derived from an actual project and are therefore subject to certain data-sharing restrictions.

ETHICAL APPROVAL

This study does not involve human participants, animals, or personal data. Therefore, ethical approval was not required.

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