Proceedings World Geothermal Congress 2023
Beijing, China, April 17 – 21, 2023

Design and evaluation of ground source heat pump for the heating and cooling system of a school building

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Keywords: Heating and cooling; Ground source heat pump; Evaluation system; Numerical simulation; Life cycle cost

ABSTRACT

As a kind of zero-carbon clean energy, geothermal heating and cooling could save the energy consumption of public buildings and reduce emissions effectively, which has the ability to realize carbon neutrality. However, the systematic analysis of the technical and economic aspects of the ground source heat pump system from a macro perspective is not comprehensive enough. This paper takes a school building as an example to design and simulate the ground source heat pump system, and then make a comprehensive evaluation of it. Firstly, four indicators were chosen from the economic, environmental protection, and energy saving aspects to establish a comprehensive evaluation system. Moreover, loads of heating and cooling were simulated in DeST. In order to meet the heating and cooling demand, a ground source heat pump system was designed for the school building. Finally, the ground source heat pump system is evaluated by the established evaluation system and compared with the conventional heating and cooling system. Results show the life cycle cost of the ground source heat pump system was 7,878,096 Chinese yuan. The volume of alternative standard coal, reduction of CO_2 emissions, and SO_2 emissions were 157.40 tons, 388.78 tons, and 3.15 tons, respectively. The comprehensive comparative analysis shows that under the condition of basically satisfying comfort, ground source heat pump system is the better heating and cooling mode for the school building, which could reduce operating costs and building energy consumption effectively. This provides recommendations for guiding the rational use of energy storage and ground source heat pump technology in school buildings.

1. INTRODUCTION

According to the Research Report released by the China Building Energy Efficiency Association (2021), the national total carbon emissions from the whole process of construction in 2018 were 4.93 billion tons, accounting for 51.3% of the country's carbon emissions. The Ministry of Housing and Urban-Rural Development predicts that the proportion of electricity consumption in building energy consumption will exceed 55% by 2025 (2022). Meanwhile, the demand for campus buildings is increasing. Campus buildings are in the field of high energy consumption in various types of energy-consuming buildings. The amount of energy consumption is quite large, and the potential space for energy saving and consumption reduction is also considerable.

It has always been a widely prevalent belief that renewable energy sources are clean and green in contrast to nonrenewable fossil fuels (Abbasi et al.,2012). Geothermal is clean and renewable energy. China has abundant geothermal resources, accounting for 1/6 of the world's total, and developing geothermal is of critical importance to China's energy mix restructuring, energy conservation, emission reduction, and environmental protection (Wang et al.,2016). Among the various technologies and methods available for harvesting geothermal energy, the ground source heat pump (GSHP) is considered to be an efficient and dominant means (Singh et al.,2019). The GSHP heating system uses seasonal temperature differences to extract the energy of underground soil from the ground space through the GSHP air conditioning system in winter and uses the ground indoor heating terminal for indoor heating. In summer, the indoor heat is taken out and released into the soil for indoor refrigeration (Han et al.,2009). GSHP is widely studied because of its environmental protection and energy saving, stability and renewable, and long multi-purpose life of the machine (Ma et al.,2007).

Kun Zhou et al. (2020) developed a detailed numerical model integrating the ground heat exchanger (GHE) and heat pump and an economic model considering economic indicators to analyze the thermal and economic efficiency of residential GSHP in China. Han et al. (2021) monitored the thermal performance of a GSHP system in a large building. The results showed that the GSHP system of this large building had high efficiency and remarkable energy-saving benefit. Sangmu Bae et al. (2022) used a numerical simulation model to analyze the performance of the GSHP system. In addition, the economic analysis and life cycle climate performance (LCCP) were compared based on the numerical analysis results. The result showed that the intermittent operation method increased the heat exchange rate of the GSHP system by 15% and the intermittent operation method could reduce the total cost by up to 18.7% (1,921 USD) compared to the continuous operation method, but the total emissions increased by up to 11.8% (793 kg CO_{2e}). Denis Garber et al. (2013) used a methodology to evaluate the economic feasibility of a hypothetical full-size GSHP system as compared to four alternative heating ventilation and air conditioning (HVAC) system configurations. Results suggest that a full-size GSHP with auxiliary backup is potentially the most economical system configuration.

As mentioned above, there are many empirical results in the research and application of GSHP technology in public buildings, but aiming at the application of GSHP in campus buildings is still less. At the same time, in the related research at home and abroad, from the macro perspective of the economy, environmental protection, and energy saving of the GSHP system for comprehensive analysis of the study is not enough. This paper takes a school building as the research object, using DeST simulation data to design the ground source heat pump system. In addition, the life cycle cost (LCC) mathematical model is used to compare the economy of the design and conventional heating and cooling schemes. Its energy saving and environmental performance indicators were also calculated. To establish a comprehensive evaluation system of building environment equipment energy system, guide the rational use of energy storage and GSHP technology in school buildings, to achieve the purpose of building an economic, energy-saving, and environmental protection building environment equipment energy system.

2. CONSTRUCTION OF EVALUATION SYSTEM

The method provided in the "Evaluation Standards" is used to evaluate the energy efficiency, environmental protection, and economic benefit of the GSHP system (GB50801,2013). According to the characteristics of the GSHP, the following four indicators are selected for evaluation to improve the overall reliability of the results.

2.1 Economic Indicators

The investigation of the market found that the general energy efficiency ratio of high, stable performance of the equipment its purchase cost is high but low operating cost, emissions, and pollution in the environmental cost is also low; Energy efficiency ratio is low, the performance is relatively unstable equipment although the purchase cost is low, usually, the operation and maintenance cost is very big, the environmental damage caused is also big, so the environmental cost is also high. Faced with this contradiction, it is necessary to balance the LCC of the air conditioning system, and comprehensively compare the initial investment, operation cost, and environmental cost of the system to choose the product with the lowest LCC. Therefore, the design concept of LCC is not only to be responsible for the investment, but also to reduce the cost of the system within the whole life cycle, and to have the overall view of the cost and the system view, which is the meaning of LCC design (Liu, 2012).

LCC refers to the sum of the cost converted to the present value in the whole life cycle of the construction system equipment, that is, the whole stage from the installation to the scrapping and dismantling of the equipment, which includes the following costs:

(1) Initial investment cost. The initial investment cost includes all costs incurred between the investigation, design, equipment procurement, construction and installation of the project construction and the operation of the system.

(2) System operation cost. System operation cost refers to the energy consumption cost caused by system operation, mainly including water, electricity, and fuel costs.

(3) Maintenance and management costs. Maintenance expenses mainly include inspection and maintenance costs, management fees, salaries of management personnel, etc.

(4) Residual value. The residual value refers to the certain residual value of the system equipment that can be recycled when the system life cycle terminates (Henry et al., 2000).

Combined with the above analysis, the mathematical model of LCC of the GSHP system is:

$$LCC = IC + \sum_{t=1}^{n} OC_t (1+i)^{-t} + \sum_{t=1}^{n} DC_t (1+i)^{-t} - RC(1+i)^{-n} \tag{1}$$

When considering the residual value of equipment and waste disposal costs offset each other and do not consider the factors of energy price changes, the mathematical model of the LCC ground source heat pump system is simplified as:

$$LCC = IC + \sum_{t=1}^{n} OC_t (1+i)^{-t} \tag{2}$$

Where *LCC* refers to the life-cycle costs, *t* is the number of years that the system has been in use, *IC* is the initial investment cost of the system, OC_t is the operation and maintenance costs of the t-year system, DC_t is the waste disposal cost of the system in year, *RC* is the residual of the system respectively, *n* is the economic life cycle of the system and equals 15 years, *i* is the discount rate and equals 8%.

2.2 Energy-saving Indicators

The energy-saving benefit of the GSHP system can be directly reflected by the substitution amount of conventional energy (Luo,2017).

In the cold season, the energy consumed by the GSHP system and the conventional system is electric energy, which can be directly compared. The average standard coal consumption of power generation is 0.4 kg/kWh to calculate the standard coal quantity that can be replaced. The standard coal quantity Tcce can be substituted in the cooling season according to the following formula:

$$Tcce = (C_1 - C_2) \bullet \Phi \tag{3}$$

Where C_1 is the power consumption of the conventional system during the cooling season, kWh, C_2 is the power consumption of the heat pump system during the cooling season, kWh respectively, φ is the conversion rate of electric energy and primary energy and equals 0.4 kg/kWh.

In the heating season, the energy consumed by the GSHP system is still electric energy, while the gas boiler consumes primary energy. It is necessary to convert the electric energy into primary energy and then compare it to obtain the alternative standard coal quantity in the heating season.

$$Thce = T_1 - C_3 \bullet \Phi \tag{4}$$

Where T_1, is the primary energy consumption of the conventional system in the heating season, kg; C_3 is the power consumption of the heat pump system in the hot season, kWh; φ is the conversion rate of electric energy and primary energy and equals 0.4kg /kWh.

2.3. Environmental Indicators

According to the relevant provisions of the environmental benefit evaluation index, the emission reduction of greenhouse gas (CO_2), and pollution gas (SO_2) can be calculated as follows (GB50801,2013).

$$Q_{co2} = 2.47 Q_{bm} \tag{5}$$

$$Q_{so2} = 0.02 Q_{bm} \tag{6}$$

Where Q_{CO2}, is carbon dioxide emission reduction, ton/year; Q_{bm} is the standard coal saving quantity, ton/year; Q_{SO2}, is sulfur dioxide emission reduction, ton/year.

3.CASE STUDY

3.1.Building Characteristics

This study selected an experimental building of Chengdu University of Technology with a total area of approximately 21,000 m^2, located in Yibin City, China. Using the meteorological parameters provided by DeST software (2006) for simulation calculation, the outdoor air parameters in Yibin are obtained as shown in Figure 1 to Figure 3.

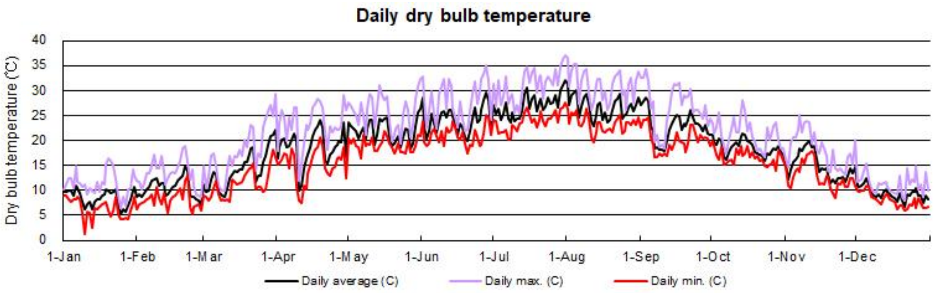

Figure 1: Annual outdoor temperature statistics in Yibin

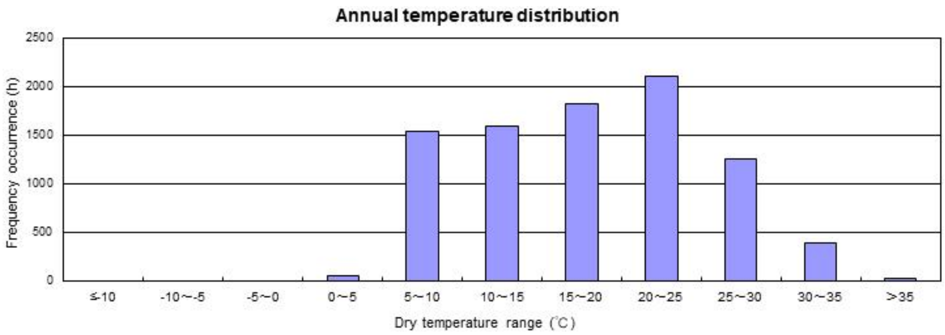

Figure 2: The statistical chart of temperature distribution throughout the year in Yibin

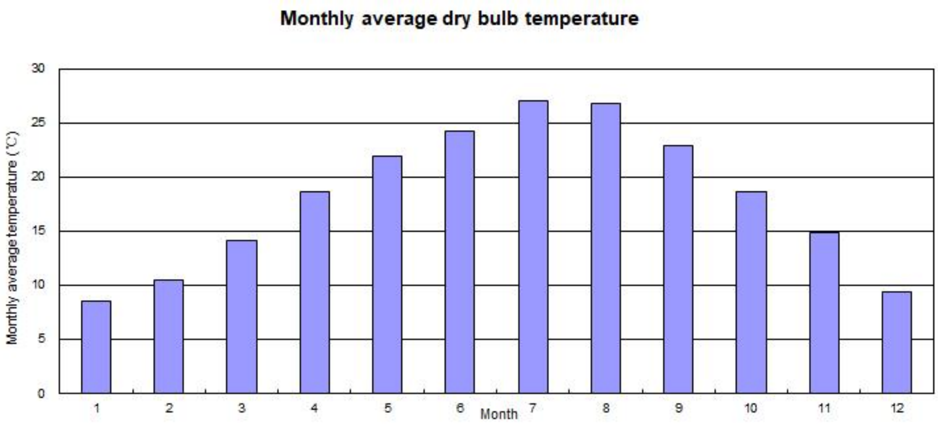

Figure 3: The statistical chart of the average monthly dry-bulb temperature in Yibin

The outdoor dry bulb temperature of summer air conditioning in Yibin is 27.1 ℃, and the number of days of summer air conditioning (CCD26) is 106 ℃·d. While the outdoor calculated temperature of winter heating is 8.5 ℃, and the number of days of the heating period (CCD18) is 1043 ℃·d. It can be inferred from the above figures that the outdoor temperature in winter is significantly higher than that in the northern central heating area, and the duration is short. The summer cooling demand of this project is much higher than that of winter heating demand.

The building loads are simulated using the building simulation software DeST-C. Using the method of establishing the dynamic model of the building thermal process, DeST comprehensively considers the heat storage and heat release of building envelope and objects, including the long-wave radiation heat transfer between the inner surfaces of each envelope and the convective heat transfer of air. Using the room heat balance method, the hourly simulation of 8760 hours a year is carried out by computer, and the annual energy consumption of the building is obtained. Among them, the summer design cooling load is 2315.72 kW, whereas the winter design heating load is 1300.45 kW. The cooling period in Yibin lasts from June 1 to October 1, whereas the heating period lasted from December 1 to February 28.

3.2. Design of Heating and Cooling System

The inlet and outlet water temperature of shallow geothermal heat transfer holes is 35/30 °C in summer and 5/10 °C in winter. Combined with cold load, heat load, and shallow geothermal heat transfer operation conditions, two heat pump units with a cooling capacity of 580 kW are selected. Specific parameters of the ground source heat pump system are shown in Table 1.

Table 1: Selection of Heat Pump Unit for Shallow Geothermal System

Operation season	Cooling/Heating Capacity（kW)	Input Power (kW)	Coefficient of Performance	Inlet and Outlet Water Temperature of Evaporation Side (℃)	Inlet and Outlet Water Temperature of Condensation Side (℃)
Summer cooling conditions	580	103	5.6	12/7	30/35
Winter heating conditions	575	134	4.3	10/5	35/45

Meanwhile, the GSHP with shallow geothermal buried GHE has the advantages of high efficiency of system operation and energy storage. It is tentatively planned that the space around the experimental building and the modern industrial college building will be used as a shallow geothermal heat transfer hole layout site. The shallow buried heat transfer hole drilling site available is about 275,000 m^2, and the number of construction holes is about 1100 according to 5 m hole spacing.

To reduce the floor area of GHE, the GHE system is designed as a vertical buried pipe, and a single U-tube parallel system is used. At the same time, to maintain the hydraulic balance between the loops, the same-equation system is adopted. Considering the energy consumption of transportation and the turbulence state of the fluid in the GHE at the same time, the project plans to select the heat conduction is better, low resistance HDPE pipe, specification De32x2.9mm.

After investigation, the buried pipe depth is designed to be 40m. The heat release of the unit borehole in summer is 50 W, and the heat absorption of the unit borehole in winter is 40 W. The calculation formulas of heat release to the soil in summer and heat release to the soil in winter are:

$$Q_S = Q_L \times (1 + \frac{1}{EER}) \tag{7}$$

$$Q_T = Q_R \times (1 - \frac{1}{COP}) \tag{8}$$

Where Q_S and Q_T are heat loss to the soil in summer and heat extraction from soil in winter, EER is energy efficiency ratio and equals 5.6, COP is coefficient of performance and equals 4.3.

According to numerical simulation based on DeST, the cooling load of the building model is 2315.72 kW in summer and 1300.45 kW in winter. Therefore, the heat discharge and heat intake between the buried pipe system and the soil is 2729 kW and 998 kW respectively. The cumulative cold and heat load ratio defined as an unbalanced load rate is calculated as 2.73. If all the heat transfer is provided by the soil, the heat gain and loss of the soil will be seriously unbalanced. The long-term operation will cause the destruction of the soil temperature field and the increase of the soil body temperature, which will lead to the increase of the inlet temperature of the heat pump main engine, the increase of the condensation temperature of the main engine, the decrease of the system performance, and even the failure of the whole air conditioning system. Therefore, it is necessary to take certain auxiliary heat dissipation measures (such as efficient cooling towers or heat recovery technology) to maintain the balance of the temperature field of buried pipe and to ensure the long-term efficient and stable operation of the GSHP system.

The design of the buried pipe is shown in Table 2. To avoid the problem of soil heat imbalance, the number of buried pipe holes in this project is designed according to winter conditions. The insufficient heat discharge in summer is supplemented by the high-efficiency cooling tower, and the cooling tower is in series with the buried pipe. Firstly, the cooling water on the water source side is heat exchanged with the outdoor air, and then the heat is exchanged with the soil through the buried pipe, to solve the problem of soil thermal imbalance. The system operating load equivalent in the summer cooling season is 0.7, and the GSHP system operating load equivalent in the winter heating season is 0.6. Combined with the operation of the project and the factors such as thermal balance and hydraulic balance of the system, considering the reserved 10 % of the underground heat transfer system, 412 underground pipe wellheads are designed. According to the formula, the cooling capacity provided by the buried pipe is 824 kW, and the cooling load borne by the cooling tower is 1086 kW.

Table 2: Design parameters of buried pipe

Operation season	Heat exchange required (kW)	Heat transfer per meter (W/m)	GHE length (m)	Pipe buried depth (m)	Number of design wellheads
Summer cooling conditions	1910	50	38200	40	955
Winter heating conditions	599	40	14975	40	374

Figure 4 and Figure5 present schematics of the GSHP system in summer and winter respectively. In winter, heat pump units absorb heat from the soil through the GHE for building heating. In summer, the heat pump units dissipate heat to the soil through the GHE under partial load conditions; when the cooling load increases or the peak load, the cooling tower is activated for heat rejection (Jing et al., 2014).

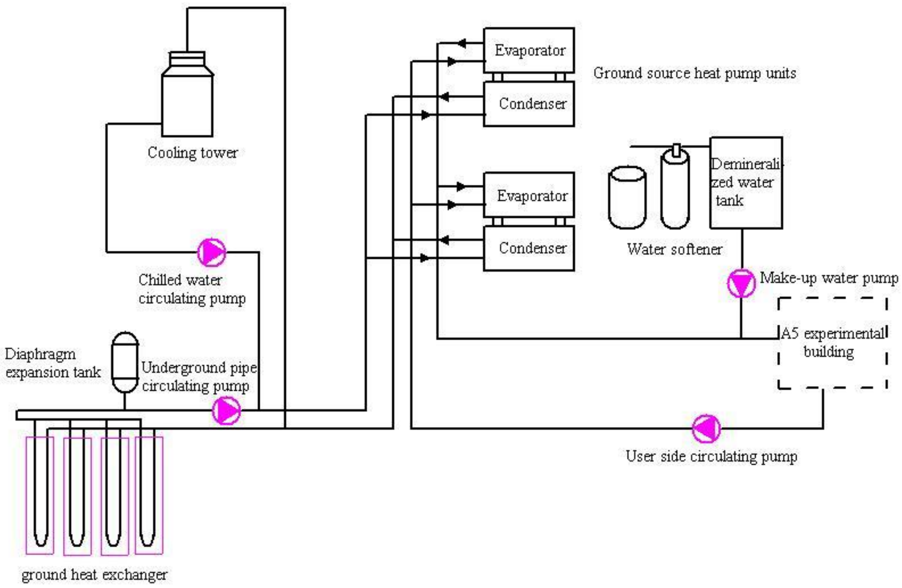

Figure 4: Schematic representation of GSHP operation in summer

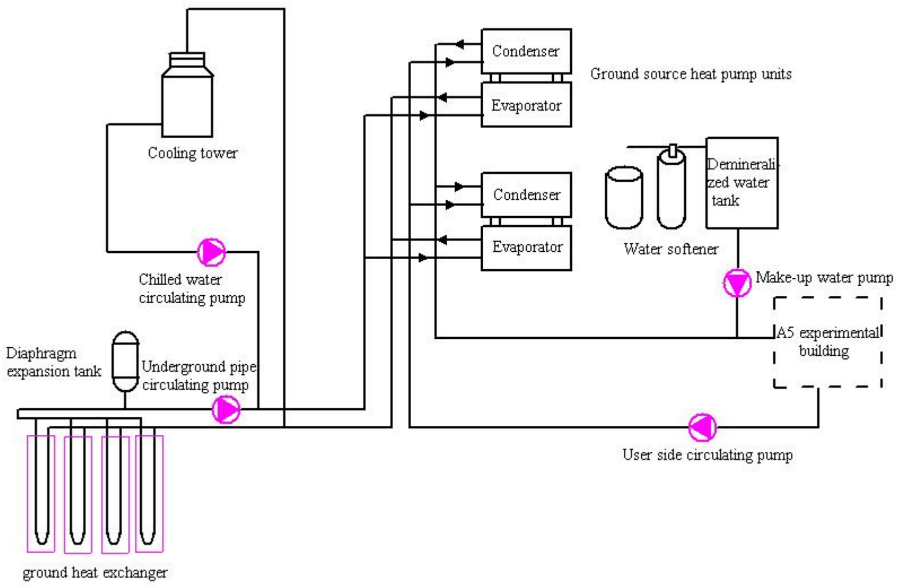

Figure 5: Schematic representation of GSHP operation in winter

4.RESULTS AND DISCUSSION

4.1.System Simulation Results

Based on the DeST-C calculation mentioned in the previous section, the statistical results of building load are shown in Table 3. The cumulative cooling load and heating load reached 1,327,862.94 kWh and 616,727.05 kWh, respectively. Fig.6. shows annual hourly unit air conditioning area load. It can be seen that the annual maximum hourly heating load is in January; the maximum hourly cooling load of the year is in August.

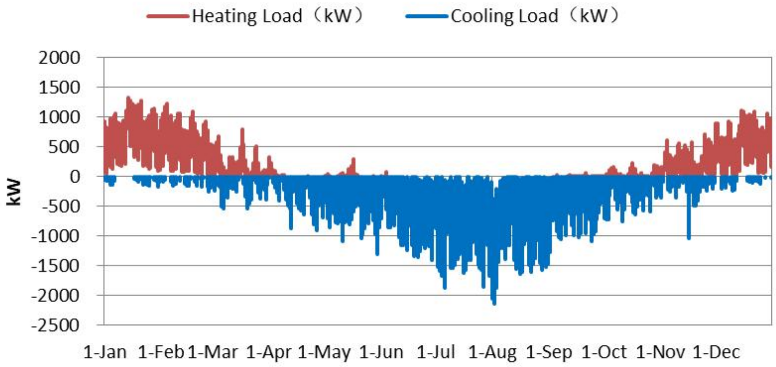

Figure 6: Hourly data of annual air conditioning load of the building

Table 3: Building load simulation results

	Item	Unit	Value
Building load summary	Annual peak heating load	kW	1,300.45
	Annual peak cooling load	kW	2,315.72
	Cumulative heating load	kWh	616,727.05
	Cumulative cooling load	kWh	1,327,862.94
Building load	Annual peak heating load	W/m^2	49.04
	Annual peak cooling load	W/m^2	87.32
	Annual heating energy	kWh/m^2	23.37
	Annual cooling energy	kWh/m^2	65.12
Building seasonal load	Heating season load	W/m^2	9.45
	Cooling season load	W/m^2	17.10

The simulation results are also obtained that the annual power consumption of GSHP system heating is 143,424.90 kWh, and the annual power consumption of GSHP system cooling is 237,118.38 kWh.

4.2.Economic Data Analysis

GSHP system mainly includes buried pipe drilling and external network part, heat pump equipment, machine room equipment and cooling tower part, and refrigeration outdoor pipe network part. In Table 4, the initial investment of the ground source heat pump and conventional heating and cooling system (chiller and gas boiler) is compared. The initial investment of the GSHP system is 4,214,226.77 Chinese yuan (CNY). Among them, GHE drilling and pipeline materials are the main costs of initial investment, a total of 412 wells were drilled outdoors to a depth of 40m.

Table 4: System initial cost

System type	Gas boiler (CNY）	Other equipment (CNY）	GHE（CNY）	Initial investment (CNY）
GSHP air condition system	0	783,090.77	3,431,136.00	4,214,226.77
Chiller and gas boiler	569,584.03	356,276.50	0	2,899,533.95

Table 5 reports the annual operation costs of the GSHP air condition system and Chiller and gas boiler. Compared with conventional heating and cooling methods， the annual operation costs are reduced by 289,088.94 CNY by using the GSHP system.

Table 5: System annual operating cost

System type	Operation season	Form of energy	Energy unit cost	Energy cost(CNY)	Annual operating cost(CNY)
GSHP air condition system	Summer	Electricity	0.82	194,436.76	312,045.26
	Winter	Electricity	0.82	117,608.50	
Chiller and gas boiler	Summer	Electricity	0.82	345,433.20	601,134.20
	winter	Natural gas	2.41	255,701.00	

The LCC of each system is calculated considering both the energy and the maintenance costs. Among them, the labor cost according to 2 project management personnel, salary is calculated at 4000 yuan per person per month, maintenance depreciation cost calculated at 10 % of the depreciation cost, equipment depreciation period of 15 years, and expected net residual rate of 4 %.

According to the above calculation results, the components of the LCC of the whole life cycle of the GSHP system are summarized in Table 6, and the LCC of the GSHP system and the conventional heating and cooling system are calculated respectively.

It can be seen that the GSHP system has lower annual operating and maintenance costs, 37.7 % lower than the chiller and gas boiler system. In addition, from the perspective of the whole life cycle of the system. The LCC of the GSHP system is 7,878,096CNY, which is 10.4 % lower than the chiller and gas boiler systems. According to the calculation results, it can be inferred that although the initial investment cost of the GSHP system is 45% higher than that of the chiller and gas boiler system, its operation and maintenance costs are lower, resulting in a lower LCC of the GSHP system. And the GSHP reliability is high, and easy to maintain, which is more suitable for such long-used school buildings.

Table 6: LCC summary results

System type	Net present value of operating and maintenance management costs in each year (1-15) (CNY)														
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
GSHP air condition system	448,094	447,349	446,613	445,887	443,973	443,298	442,631	441,974	441,325	440,684	440,052	439,428	438,812	303,690	168,569
The LCC of the GSHP air condition system is 7,878,096 CNY.															
Chiller and gas boiler	718,828	718,338	717,854	717,377	716,905	716,440	715,981	715,528	715,081	714,640	714,204	713,774	713,350	414,666	298,684
The LCC of Chiller and gas boiler is 8,795,735 CNY.															

4.3. Energy saving and environmental data analysis

The energy consumption of the GSHP system, water source heat pump system, and conventional energy system (chiller and gas boiler) is converted to standard coal for comparison in Table 7. The power consumption of the equipment and terminal equipment in the GSHP system during the cooling season is 237,118 kWh, and the power consumption of the chiller is 421,260 kWh; in winter, the power consumption of equipment and terminal equipment in the GSHP system is 143,425 kWh, and the gas consumption of gas boiler is 106,100 Nm3. The standard coal conversion coefficient of natural gas is 1.33 kg/kWh (GB2589,2020). Therefore, the use of a ground source heat pump system saves a total of 157.40 tons of standard coal. Water chillers and gas boilers consume a lot of coal for heating, which clearly shows the energy efficiency of the GSHP system.

Table 7: Saved primary energy, CO2 emissions, and SO2 emissions

System type	Saved Primary Energy (t)	Avoided CO_2 Emissions (t)	Avoided SO_2 Emissions (t)
GSHP air condition system	157.40	388.78	3.15

In summary, the environmental and energy-saving benefits of the GSHP system are significant. The energy saving rate of the GSHP system is close to 50 %. Meanwhile, the reduction of CO_2 emissions helps to alleviate the greenhouse effect. SO_2 and other acid deposition substances reduce the occurrence of acid rain (M. Beér et al., 2000). The ground source heat pump system should be developed in the direction of using clean electricity. By combining with other feasible energy-saving measures, the resource consumption of the power generation system and the emission of pollutants should be reduced to maximize the environmental benefits of the GSHP system.

5.CONCLUSION

This study designed a GSHP system for both heating and cooling in school buildings in Yibin, China, and a relatively perfect comprehensive evaluation system of GSHP heating and cooling system is established to analyze the system scheme. The analyses show that:

(1)The project assessed a school building of 21,000 square meters. The building was modeled by DeST software to calculate the hourly load throughout the year. The simulation results showed that the summer design cooling load is 2315.72 kW, whereas the winter design heating load is 1300.45 kW, which indicated that the design should focus on solving the problem of unbalanced heating and cooling load of the building to increase the life of the GSHP system.

(2)The initial investment, operation cost, and maintenance management cost of the GSHP system and conventional heating and cooling system were calculated, and the life cycle cost of 15 years was calculated based on these results. The LCC of the GSHP system is 7878096.75 CNY, and the LCC of the chiller and gas boiler system is 8795735.96 CNY. Though GSHP has a higher initial investment cost, its LCC is 10.4 % lower than chiller and gas boiler systems.

(3)The GSHP system saved the equivalent of 157.40 tons of standard coal, reducing CO_2 and SO_2 by 388.78 and 3.15 tons, respectively. The system had a good energy-saving effect and can make important contributions to protecting the local environment.

In general, the ground source heat pump system can realize the demand for heating and cool at the same time. It has a good economy, environmental protection, and energy saving, and has good development prospects. Although this project also verifies that it has certain advantages, it still needs to be studied for the load characteristics of campus buildings and the intermittent use of classrooms. There are still many constraints on its promotion and wide application on campus.

ACKNOWLEDGMENTS

This work was supported by the Chengdu Municipal Bureau of Science of Technology (2021-RK00-00315-ZF and 2021-RK00-00320-ZF), and the Sichuan Mineral Resources Research Center (SCKCZY2022-YB015), and the China Scholarship Council (202108510094).

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