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Original Article

Optimization of Phase Change Thermal Storage Coupled PV/T Water Source Heat Pump Heating System

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Abstract:
Aiming at the low-carbon transformation of China's heating system and the promotion of the rapid development of renewable energy, a set of low-carbon heating system coupled with phase-change thermal storage tank, solar photovoltaic photovoltaic solar thermal equipment and water-source heat pumps is designed, and a comparative analysis is carried out with the conventional solar geothermal energy combined heating system in terms of system performance. Using TRNSYS software to build a heating system model, with a dormitory in Xi'an City as the research object, the payback period and the system energy consumption coefficient as the objective function, and the key system equipment parameters such as the solar equipment area as the decision variables, the system was optimized using the NSGA-II algorithm for multi-objective optimization and the TOPSIS method to find the optimal solution. The optimization results show that the designed system has a shorter payback period and lower system energy consumption coefficient compared with the conventional solar geothermal energy combined heating system, and a comparative analysis of the optimal solutions searched for shows that the designed system can make better use of the low-grade energy sources and has a higher solar energy utilization efficiency.

Keywords: Phase change energy storage, Solar energy, Water source heat pump, NSGA-II, System simulation

1. Introduction

With the rapid development of China's industry, energy consumption has grown rapidly. Currently, 80% of energy demand comes from fossil fuels. Meanwhile, the excessive consumption of fossil fuels has led to a continuous decline in energy reserves. The greenhouse gases and pollutant emissions produced by the combustion of fossil fuels have caused serious environmental problems. In 2009, China surpassed the United States to become the world's largest energy consumer. In 2023, China's energy consumption accounted for 26.5% of the global total, and its carbon dioxide emissions accounted for 31% of the total. Both the total consumption and the total carbon emissions were much higher than those of other major economies in the world [1][2][3][4]. To overcome these environmental problems that hinder sustainable development, energy consumption is more inclined to adopt new technologies and make more effective, useful, and extensive use of clean and renewable resources. Today, the energy consumption of buildings accounts for 40% of the total energy supply, and heating consumption takes up the largest share of building energy consumption, approximately 55% in the United States, 70% in China, and 80% in Europe [5]. In addition, fossil fuels and electricity based on fossil fuels constitute the main energy supply for heating applications [6]. On the other hand, solar energy is a renewable, clean, and easily accessible energy source that can be used to maintain environmentally friendly and sustainable systems. Geothermal energy is the heat energy from the interior of the Earth, mainly derived from the Earth's thermal radiation and the decay process of radioactive substances. As a clean and renewable energy source, geothermal energy can provide long-term and stable heat energy for heating and is particularly suitable for the heating needs of cold regions [7]. Taking advantage of the abundant solar energy resources and the stability of geothermal energy, the heating demand is met through the solar-ground source heat pump system (SGHP system) to improve the performance of the heat pump and reduce the consumption of fossil fuel electricity [8].

Solar heating technology has developed rapidly in China, but solar energy is limited by natural conditions such as day and night and season, so many studies focus on multi-source heating. Sun et al. [9] established a model of typical buildings and two heating strategies in TRNSYS, and optimized it around multiple objectives of solar guarantee rate, heat pump COP, and soil heat supply rate. The results showed that the optimized control strategy of the geothermal solar heating system had the following characteristics: system performance. Zhu et al. [10] established a phase-change thermal storage coupled solar heat pump heating system, optimized the solar collector area, volume of phase-change thermal storage tank and heating end heat exchanger of the system, and the results showed that adding appropriate volume of phase-change thermal storage tank in the system could reduce the operating cost of the system. Zhang et al. [11] established a solar-ground source heat pump phase-change thermal storage heating system model based on low current drive, and analyzed the soil heat imbalance problem of the system; and the results showed that the system had better soil heat balance.

Chen et al. [12] added a phase change heat storage box to the solar air source heat pump system. The experimental and simulation results show that the adoption of a phase change heat storage box can effectively solve the frosting problem of the evaporator in the air source heat pump, improve the COP of the heat pump under extreme weather conditions, and also enhance the energy efficiency of the system. The operating cost for the entire heating season is approximately 55.4% of that of a gas boiler and 65.6% of that of an air source heat pump. Griesbach et al. [13] conducted a numerical study on the possibility of combined heat pump ice energy storage systems without solar energy benefits and the utilization of waste heat generated within non-residential buildings. A detailed numerical model of the ICE energy storage box was developed, and the numerical realization was analyzed and verified. To consider the changes of the solid-liquid phase, the enthalpy method based on specific heat capacity was adopted to analyze and verify the numerical realization. The results show that the error between the mathematical model of the ICE ice energy storage system under the mathematical model and the actual experimental model is only 2%, and the mathematical simulation of phase change energy storage is feasible. Zhu et al. [14] established a phase change heat storage coupled solar heat pump heating system and optimized the area of the solar collector, the volume of the phase change heat storage tank and the heat exchanger at the heating end of the system. The results showed that adding an appropriate volume of the phase change heat storage box in the system could reduce the operating cost of the system. Yu et al. [15] added a phase change heat storage device based on time-sharing control in the PV/T- heat pump heating system, established a simulation model of the PV/T collector - heat pump - phase change heat storage - electric coupling combined heating system, and optimized the main equipment parameters such as the inclination Angle and area of the PVT collector and the heating capacity of the heat pump. The optimization results show that compared with the common hot water storage tank system, the phase change hot water storage tank system can significantly improve the system performance. Ma et al. [16] established a numerical model of the phase change heat storage coupled heat pump heating system based on the dynamic hourly heat load and meteorological conditions of an industrial building in Xilinhot City, and analyzed the thermal physical characteristics of the heat storage device and the economy of the multi-energy complementary heating system. The results show that the phase change energy storage device with a filling rate of 75% has the shortest payback period of investment, which only requires 6 years. Jin et al. [17] used an experimental setup mainly composed of solar collectors with a total area of 2 m2 and an air source heat pump with a maximum capacity of 2 kW to evaluate the adaptability of phase change materials to solar heat pumps and the feasibility of the heating system. The results showed that, compared with the single heating mode, the overall efficiency of the system in the combined heating mode increased by approximately 57.5%. The volume of the phase change heat storage box is reduced by approximately 21%. Maria et al. [18] added phase change materials to the solar heat pump heating system to heat a 100-square-meter ordinary building in Athens. The results showed that using a phase change material layer on the floor heating system could reduce the heating load by approximately 40% and decrease the system's power consumption. Among them, the FPC system reduced it by 42% and the PVT system by 67%. The PCM photovoltaic system has decreased by 48%.

Photovoltaic and solar thermal equipment (Photovoltaic Thermal Equipment, PV/T) has higher solar energy utilization efficiency than conventional photovoltaic cells and collectors, and its main principle is to absorb and utilize the heat of photovoltaic cells while cooling photovoltaic cells with cooling water [19]. Liu et al. [20] established a PV/T coupling system with a ground source heat pump and compared it with a ground source heat pump system. The results show that the introduction of PV/T can effectively reduce the fluctuation of buried pipe outlet temperature and is conducive to the heat balance of the land. Mi et al. [21] established a PV/T heat pump integrated energy system and conducted annual operation performance prediction in 35 cities in typical climatic zones. The results show that ambient temperature and wind speed have a great impact on system performance, and the system performance is higher when operating in severe cold areas in China. The experimental research results of Terashima et al. [22] on PV/T solar panels show that the higher the output hot water temperature of PV/T equipment, the lower the heat collection efficiency and power generation efficiency.

To improve the utilization efficiency of solar energy and reduce the cost of solar heating, this paper proposes a set of heat supply systems combining a phase change storage box, PV/T, and water source heat pump[23][24]. When the return water temperature after PV/T equipment absorbs solar energy during the day is high, the system uses a water source heat pump to store heat in the phase change storage box and release it at the peak of water consumption at night to reduce the power consumption of the system[25]. And by using the characteristics of the stable outlet temperature of the phase change storage tank, a series of storage tanks can reduce the return water temperature of the heat pump and increase the COP of a heat pump. The selection of initial system parameters will affect the analysis results. In this paper, the NSGA-II algorithm is used to carry out multi-objective optimization design of system configuration and operation parameters, and the Pareto frontier is used to compare the advantages and disadvantages of phase-change thermal storage coupled PV/T water source heat pump heating system and conventional solar and geothermal combined heating system. The optimal solutions of the two systems are compared and analyzed by the TOPSIS method, which makes the analysis results more objective.

2 System Design

2.1 System Composition and Operation Mode

The system proposed in this paper is mainly composed of PV/T equipment, phase change heat storage box, water source heat pump, buried pipe, heat storage tank, circulating water channel, circulating pump, and control valve etc. The system design is shown in **Fig. 1**.

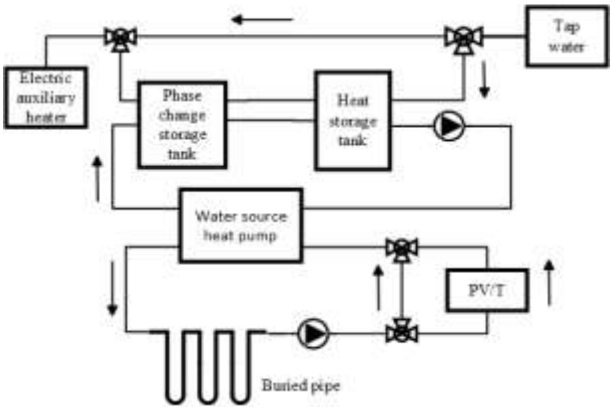

Fig. 1 System design drawing

System operation mode: (1) When the solar radiation intensity is low, the system uses geothermal energy and water source heat pump to heat the user; (2) When the solar irradiation intensity is high, the hot water collected by the PV/T equipment is first used as the low temperature heat source of the water source heat pump, for the phase change heat storage box and user heating, and then for the buried pipe. The system uses a series of heat storage tanks to replenish the tap water twice for heat exchange, to reduce the heat pump return water temperature, increase the heat pump COP, and reduce power consumption. For the power generated by photovoltaic cells in the system, this paper assumes that the operation mode of "self-use, surplus online" is adopted. In this mode, photovoltaic cells are connected to the grid. When the power generation of photovoltaic cells is not enough to maintain the operation of the system, the insufficient power is directly provided by the power grid, which can improve the stability of the system's operation and reduce the operating cost of the system.

2.2 Load

The total number of people in the dormitory is 500, and the per capita water consumption is designed to be 80L/d, the daily hot water consumption is 40000L/d, and the hot water temperature is 50℃, as shown in **Fig.2**. The proportion of domestic water consumption varies with time, and the central water consumption time ranges from 20.00 to 23.00, and the temperature of tap water replenishment varies with the season, with the lowest being 7.3℃ and the highest being 24.5℃. For detailed data, refer to Design Standards for Water Saving of Civil Buildings [26].

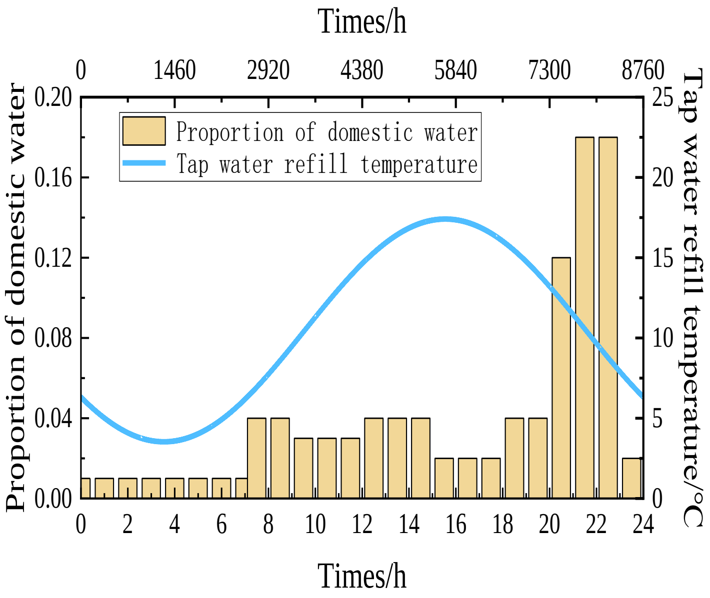

Fig. 2 Proportion of domestic water and temperature of tap water replenishment

3 System simulation model

The heating system model was established using TRNSYS software. The main components used include the water source heat pump module Type 927, the PV/T equipment module Type 50D, the vacuum tube collector Type 71, the buried pipe module Type 557A, the water pump module Type 110, the phase change heat storage box module Type 1336 and the hot water storage tank module Type4. The model of the phase change heat storage coupled PV/T water source heat pump heating system and the model of the conventional solar and geothermal combined heating system before improvement are shown in **Figs. 3** and **4**, respectively. The rated parameters of the water source heat pump used in the system are shown in **Table 1**.

Table 1 Parameters of water source heat pump

Argument	Numerical value
Rated heat production / kW	100
Rated power / kW	27
Rated mass flow of condenser / ($m^3 \cdot h^{-1}$)	15
Rated mass flow of evaporator / ($m^3 \cdot h^{-1}$)	12

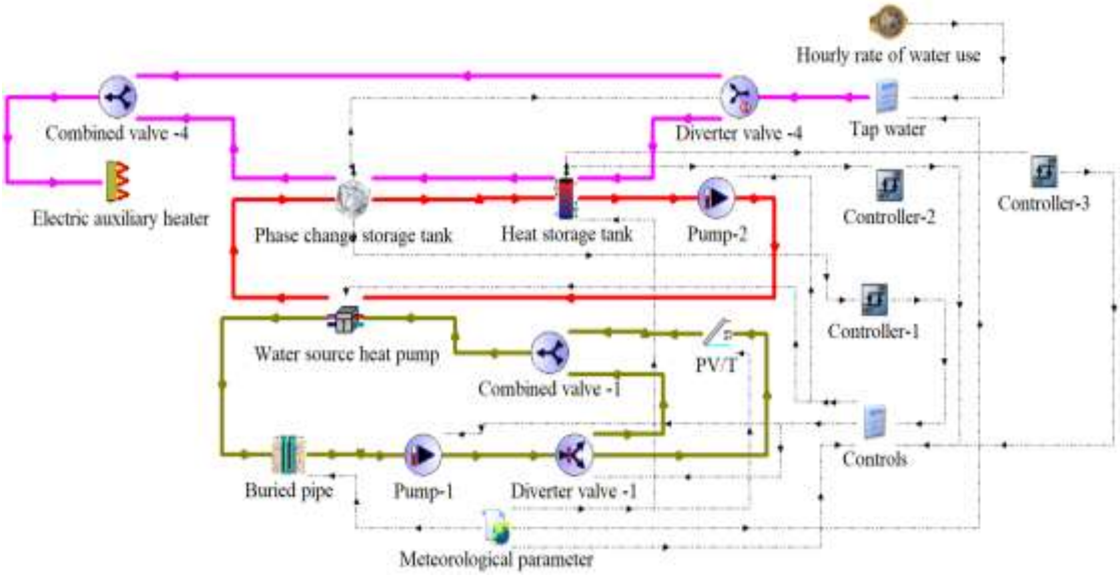

Fig.3 Modeling of phase change thermal storage coupled PV/T water source heat pump heating system

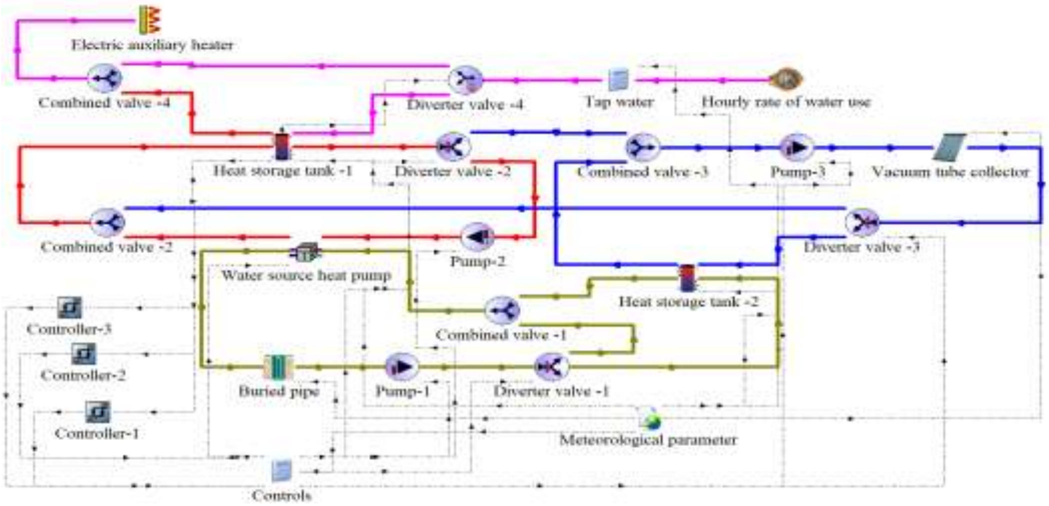

Fig.4 Modeling of solar geothermal combined heating system

3.1 PV/T Device Model

The energy destinations of PV/T equipment are classified as: thermal energy converted by solar thermal devices, electrical energy converted by photovoltaic devices, and energy dissipated into the environment, that is:

$$G = \gamma G + \alpha G \qquad (1)$$

$$\alpha G = E_{pv} + q_T + q_L \qquad (2)$$

Where: G is the total radiation of solar energy, J; γG is reflected radiant energy, J; αG is the absorbed radiation energy, J; q_L is the heat dissipated to the outside world, J; E_{pv} is the converted electrical energy, J; q_T is the converted heat energy, J.

When actually calculating the photoelectric conversion efficiency, since the photoelectric conversion efficiency of photovoltaic cells decreases as the temperature of the cells themselves increases, the thermal attenuation of the power generation efficiency needs to be taken into account. The calculation formula for its photoelectric conversion efficiency is as follows:

$$\eta_m = \eta_{m.ref} - \mu_t (t_{pv} - t_{ref}) \tag{3}$$

Where: η_m is the actual photoelectric conversion efficiency; $\eta_{m,ref}$ is the photoelectric conversion efficiency under ideal conditions, which is taken as 17% in this paper.; t_{pv} is the actual operating temperature of the battery, °C; t_{ref} is the ideal operating temperature, 25°C; μ_t is the temperature attenuation coefficient of power generation efficiency, which is taken as 0.5% in this paper.

3.2 Phase Change Heat Storage Box Model

The phase change heat storage material adopted in the phase change heat storage box is No. 52 paraffin [11], and its thermophysical properties are shown in **Table 2**.

Table 2: Parameters of phase change materials

Argument	Numerical value
Liquid density/kg • m^{-3}	780
Solid density/kg • m^{-3}	820
Specific Heat Capacity/kJ • (kg • K)$^{-1}$	2.4
Latent heat of phase transformation/ kJ • kg^{-}	230
Phase transition temperature / °C	52~54
Thermal conductivity / W • (m • K)$^{-1}$	0.78

principle of phase change heat storage is to store heat by utilizing the enthalpy changes of materials during the phase transition process. During the heat absorption/release process, the temperature variation range of the material is relatively small; that is, phase change heat storage has isothermal characteristics and a high energy heat storage density. The heat transfer equation between the heat exchanger of the phase change heat storage box model and the phase change material is:

$$Q_{hx} = m_{hx} C(t_{hx,out} - t_{hx,in}) = m_b \frac{dh_b}{dt} \tag{4}$$

Where: Q_{hx} is the heat exchange capacity of the heat exchanger, kW; m_{hx} represents the flow rate of the working medium in the heat exchange pipeline, kg•s^{-1}; C is the specific heat capacity of the heat exchange working medium. In this paper, water is used as the working medium, 4.19kJ•(kg•K)$^{-1}$; $t_{\mathrm{hx,out}}$ is the outlet temperature of the fluid in the heat exchanger, °C; $t_{\mathrm{hx,in}}$ represents the fluid inlet temperature of the heat exchanger, °C; m_{b} represents the mass flow rate of the phase change material during melting, kg•s^{-1}; h_{b} represents the enthalpy value of the phase change material, kJ•kg.

4. System Optimization and Operation Analysis

4.1 Optimization Parameters and Objectives

The heating system was simulated based on the typical annual meteorological condition data in TMY2 format collected by the meteorological stations provided in the meteorological software Meteonorm. The key parameters affecting the system performance are the area of solar equipment, the volume of the phase change heat storage box, the rated heating power of the heat pump, the number of underground pipe holes, and the inclination Angle of the collector. These five parameters are selected as the optimization decision variables for system optimization. The optimization objectives include the system investment payback period, considering the economy and the system energy consumption coefficient, and considering the environmental protection performance of the system.

The initial investment of the system is mainly used for purchasing and installing PV/T equipment, water source heat pump units, hot water storage tanks, phase change energy storage boxes (the price of phase change heat storage boxes is calculated based on the volume of the required phase change heat storage materials), underground pipes, water pumps and their accessories, etc. Considering the actual situation, the initial investment of the system is shown in **Table 3**.

Table 3. Initial cost of system equipment

Equipment	Initial cost	Equipment	Initial cost
PV/T	1000 yuan/ m^2	Water source heat pump	850 yuan/ kW
Vacuum tube collector	950 yuan/ m^2	Hot water storage tank	680 yuan/ m^3
Phase change heat storage materials	6600 yuan/ m^3	Manifold valve	3000 yuan per piece
Water pumps and their accessories	2.2 ten thousand/ per one	Underground pipe	1.9 ten thousand yuan per hole
Electric auxiliary heater	20000 yuan		

The economic efficiency of a heating system can be measured by the payback period [10], taking into account both the construction cost and the operation cost of the system comprehensively. The calculation formula is as follows:

$$PP = \frac{\mathrm{In}(C_{\mathrm{F}} / (C_{\mathrm{F}} - r \times CI))}{\mathrm{In}(1+r)} \qquad (5)$$

$$C_{\mathrm{F}} = \int_0^{\mathrm{t}} c\left(\left(1-\varepsilon\right)E_{\mathrm{pv}} - E_{\mathrm{h}}\right)dt + Y_{\mathrm{h}}M_{\mathrm{h}} \qquad (6)$$

Where: PP represents the investment payback period, which is years; C_{F} represents the net annual income of the system, amounting to ten thousand yuan; r is the discount coefficient, which is taken as 3%. CI The initial investment, amounting to ten thousand yuan c, is the local electricity price,0.5 yuan/kW•h; ε represents the loss rate of photovoltaic power generation, calculated at 30%; E_{pv} represents photovoltaic power generation, kW; E_{h} represents hourly power consumption, kW; Y_{h} is the revenue from hot water supply. In this paper, it is taken that 0.02 yuan /L M_{h} is the hot water supply volume, L.

The energy-saving effect of the system is measured by the system energy consumption coefficient, and its calculation formula is as follows:

$$S = \frac{\int_0^t \left(E_{\mathrm{h}} - \left(1-\varepsilon\right)E_{\mathrm{pv}}\right)dt}{\int_0^t mC(t_{\mathrm{s}} - t_{\mathrm{in}})dt} \qquad (7)$$

Where: S is the energy consumption coefficient of the system; m represents the hourly mass flow rate of hot water supply,kg•h^{-1}; t_{s} represents the hourly hot water supply temperature, °C; t_{in} represents the hourly water replenishment temperature of tap water, °C.

4.2 Optimization Results and Analysis

The Pareto frontier was obtained through the NSGA-II algorithm. To find the optimal point in the Pareto frontier, the TOPSIS method was used to evaluate each solution. The evaluation ranking selected the optimal point and the optimal points of each optimization objective as shown in **Fig. 5**. Overall, the payback period of the phase change heat storage coupled PV/T water source heat pump heating system is relatively short. The relatively low energy consumption coefficient of the system indicates that the economic and environmental benefits of the phase change heat storage coupled PV/T water source heat pump heating system are higher.

The optimal solutions selected through evaluation and ranking are shown in **Table 4**. After optimization, some parameters of the two systems differ significantly. The main reason is that in the night phase change heat storage coupled PV/T water source heat pump heating system, the phase change heat storage box and the heat pump jointly provide heat, making the rated heating capacity of the heat pump required by the system and the dependence on buried pipes lower. Compared with the conventional solar and geothermal combined heating system, the payback period of the phase change heat storage coupled PV/T water source heat pump heating system has increased by 0.05 years, and the energy consumption coefficient of the system has decreased by 0.038.

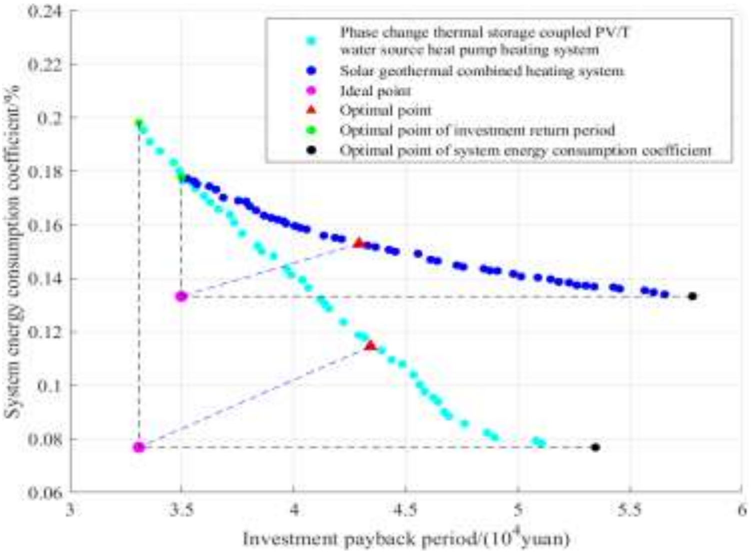

Fig.5 Optimization result diagram of the system

Tab.4 Ranking results of TOPSIS evaluation

Parameters	Phase change heat storage coupled PV/T water source heat pump heating system	Conventional solar and geothermal combined heating system
Investment payback period/year	4.34	4.29
System energy consumption coefficient	0.115	0.153
Solar energy equipment area /m2	668	545
The number of underground pipe holes	5	9
Rated heating power of the heat pump/kW	72	96
Volume of phase change heat storage box/m3	10.85	—
Collector inclination Angle	24	26

The two systems were simulated using the optimized parameter values. The performance characteristics of the systems were simulated and calculated. The operation results of the systems are shown in Table 5. Due to the large usage area of the PV/T equipment in the phase change heat storage coupled PV/T water source heat pump heating system, the initial investment of the system is 56,000 yuan higher than that of the conventional solar and geothermal combined heating system. Compared with the conventional solar and geothermal combined heating system, the power consumption of the electric auxiliary heater of the phase change heat storage coupled PV/T water source heat pump heating system has decreased by 2950 kWh, and the net power consumption is lower by 22,194 kWh. The main reason is that the heat storage density of the phase change heat storage box is relatively high. This enables the system to have a lower dependence on the electric auxiliary heating device when the thermal load is relatively high. The electrical efficiency of PV/T equipment is relatively high, and the available power generation accounts for 51.87% of the power consumption. The optimized results show that the phase change heat storage coupled PV/T water source heat pump heating system has better energy-saving benefits.

Tab.5 System operation results

Parameters	Phase transformation	Conventional

Initial cost/ten thousand yuan	103.9	98.3
Power consumption of electric auxiliary heater /(kW• h)	5715	8665
Power consumption/ (kW • h)	138588	88898
Power generation/(kW • h)	71884	—

Among the two heating systems, the water source heat pump is a device that utilizes low-grade energy sources such as geothermal energy and solar energy. The magnitude of its COP has a significant impact on the overall performance of the system. As shown in **Figs. 6** and **7**, the hourly COP and the average annual COP of the water source heat pumps of the two systems are presented. The hourly COP of the phase change heat storage coupled PV/T water source heat pump heating system is concentrated between 3.5 and 5.5, and the average annual COP is 4.46. The hourly COP of the conventional solar and geothermal combined heating system is concentrated between 3.5 and 5.2. The average COP for the whole year was 4.44, indicating that the phase change heat storage coupled PV/T water source heat pump heating system is relatively dependent on ground source heat pumps, and at the same time, the average heat collection efficiency of PV/T equipment is relatively low.

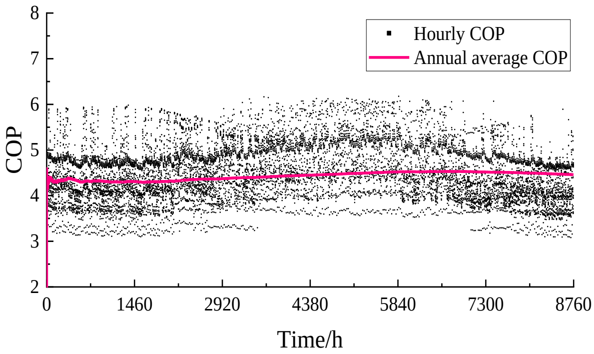

Fig. 6 Water source heat pump COP of phase change thermal storage coupled PV/T water source heat pump heating system

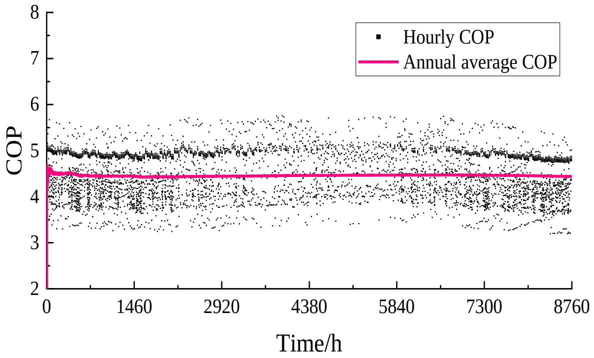

Fig.7 Water source heat pump COP of conventional solar geothermal combined heating system

The heat collected by the PV/T equipment is first passed through the water source heat pump to increase the COP of the water source heat pump and reduce its power consumption. The excess heat is stored through the ground pipe system, and when passing through the ground pipe, the fluid is cooled. The temperature of the fluid returning to the PV/T equipment is reduced, which lowers the battery temperature and is conducive to increasing the power generation. As shown in **Figs. 8** and **9**, the electrical efficiency of PV/T equipment is concentrated between 11% and 15%, the thermal efficiency is concentrated between 25% and 55%, and the thermal efficiency of vacuum tube collectors is concentrated between 30% and 80%. The overall solar energy utilization efficiency of PV/T equipment is higher than that of vacuum tube collectors. The main reason is that the heat collection temperature of PV/T equipment is lower, resulting in a smaller normalized temperature difference of the equipment. Relatively high heat collection efficiency; The heat collection efficiency of vacuum tube collectors is widely distributed. The main reason is that when vacuum tube collectors store heat for the soil, the temperature of the fluid inside the tubes is relatively low, and the thermal efficiency is greatly improved.

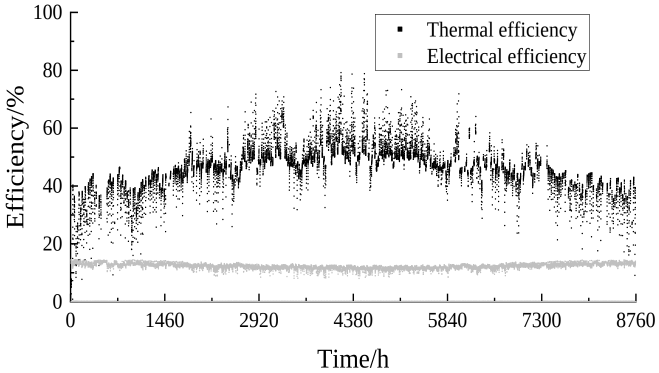

Fig.8 Thermal/electrical efficiency of PV/T equipment

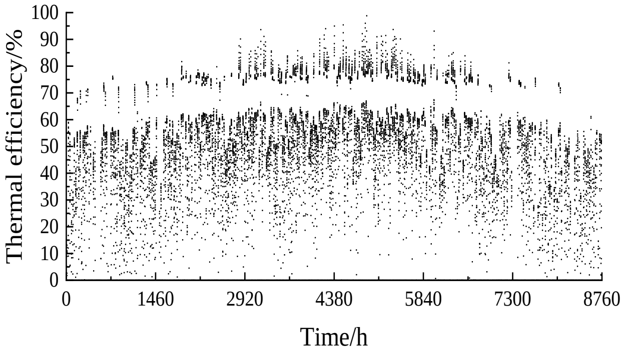

Fig.9 Thermal efficiency of vacuum tube collector

5 Conclusion

(1) A phase change heat storage coupled PV/T water source heat pump heating system was designed, and a conventional solar geothermal energy heating system was established for comparative analysis. The Pareto front after comparison and optimization shows that the phase change heat storage coupled PV/T water source heat pump heating system has a shorter investment payback period, a lower system energy consumption coefficient, and a simpler structure.

(2) The two heating systems were simulated using the optimized parameter values, and the performance characteristics of the systems were simulated and calculated. The results show that the initial cost of the phase change heat storage coupled PV/T water source heat pump heating system is relatively high, while the net power consumption is 22,194 kW•h lower than that of the conventional solar and geothermal combined heating system, which has better energy-saving benefits.

(3) By comparing the COP of the water source heat pumps of the two systems, it is found that the overall heat collection efficiency of the PV/T equipment is relatively low, and the phase change heat storage coupled PV/T water source heat pump heating system is more dependent on the ground source heat pump. The comparison of the thermoelectric efficiency of the solar equipment in the two systems indicates that the overall solar utilization efficiency of the PV/T equipment is higher than that of the vacuum tube collector.

Future Work

This paper conducts a comprehensive analysis of the phase change heat storage box coupled with the solar organic Rankine cycle heating system. However, there are still some deficiencies that need further discussion, as detailed below:

(1) The phase change heat storage box coupled with a solar organic Rankine cycle heating system studied in this paper only analyzes one area of Hohhot City and one typical application scenario of student dormitories. However, the climatic conditions of different regions and the load characteristics of typical application scenarios will have a significant impact on the design and operation performance of the system. Therefore, it is necessary to analyze multiple regions and different types of buildings to prove the universality of the system.

(2) The control strategy of the phase change heat storage box coupled with the solar organic Rankine cycle heating system in this paper is relatively simple, and the system performance is somewhat reduced. It is necessary to reduce the simulation step size of the system and optimize the control strategy of the system to cope with different operating environments, so that the simulation results of the system are closer to the actual application scenarios.

Acknowledgments

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