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Optimization of a Geothermal Heating System Coupled with Energy Storage for Office Building Heating with Consideration of Time-of-Use Electricity Prices

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ABSTRACT

In this paper, a geothermal heating system coupled with energy storage for office building heating has been studied. Optimization was carried out based on time-of-use electricity prices. The aim of this study is to lower the system's operation cost and to have better techno-economic performance. By choosing the minimum levelized energy cost (LEC) as an objective function, the optimal values of 4 decision variables have been determined by using the Genetic Algorithm. 12 scenarios have been investigated. Comparison shows that the optimal energy storage ratio of the coupled heating system is between 23% and 25% in most scenarios. It has been found out that the energy-storage tank price, heat pump price, peak-valley electricity price difference and lower limit temperature of the energy-storage tank have obvious influence on the optimal energy storage ratio. Water pump price and heat exchanger price have little influence on the optimal energy storage ratio. The results obtained in this study are considered to be useful for the application of using geothermal energy for building heating.

Keywords: geothermal heating system, energy storage, optimization, time-of-use electricity prices, Genetic Algorithm, decision variables, levelized energy cost

1. INTRODUCTION

The building energy consumption in China is an important part of the total energy consumption, which is expected to rank first in the total energy consumption by 2030 [1, 2]. Therefore, it is urgent to use clean energy for heating in cities and towns. Geothermal energy is clean and renewable, which can be widely used for heating as well as for power generation [3, 4]. According to the long-term heat-taking characteristic of geothermal energy, the intelligent heating scheme is helpful to the popularization of geothermal energy.

Applications of geothermal energy systems with energy storage have been studied previously. Alexander et al. (2015) and Glembin et al. (2015) put forward some problems that should be considered when designing a composite system [5, 6]. Benli and Durmuş (2009) studied the greenhouse system and found that the ground-source heat pump (GSHP) system with energy storage has a higher COP [7]. Lv et al. (2016) found that hybrid systems could save more than one-

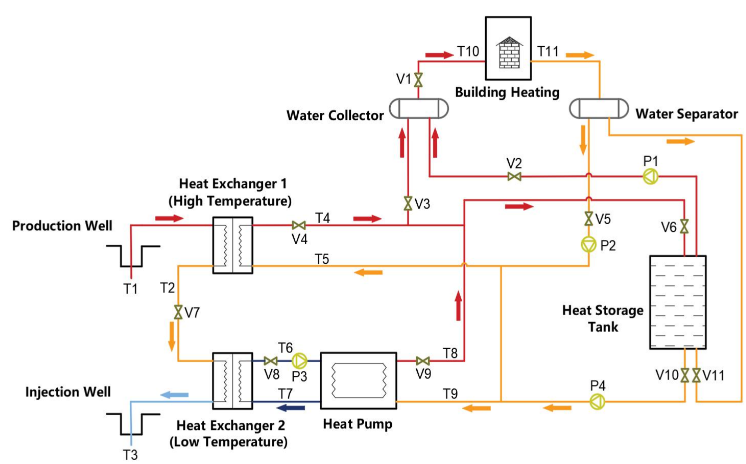

Fig. 1 Energy storage-geothermal coupled heating system

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third of the operating costs of conventional GSHP systems [8]. In addition, Jung et al. (2017) established a heat pump heating system with a heat storage device, and discussed the operation results under the condition of a fixed tank size [9].

However, studies on a geothermal heating system coupled with energy storage for office building seem weak. In this paper, a model of a geothermal heating system integrated with an energy storage unit for an office building has been established, based which optimal design and optimal operation have been carried out by considering different time-of-use electricity prices and equipment prices.

2. MODELS

2.1 Coupled energy storage-geothermal heating model

In this study, a coupled geothermal-and-energy storage heating system for a 650m^2 office building in Xianxian area (Hebei, China) has been simulated, with the day and night load variation ranging from 40W/m^2 to 70W/m^2 during the design week. The coupled heating system and its main equipment are shown in Fig.1. V1 to V11 represents 11 valves in the system as shown in Fig.1. P1 to P4 represents the 4 water pumps. T1 to T11 represents the 11 temperature measurement locations.

In this system, the high-temperature geothermal water from the production well flows through the Heat Exchanger 1 (High Temperature) and the Heat Exchanger 2 (Low Temperature) to complete the two-stage heat transfer. After heat exchange in the Heat Exchanger 2, the heat of the circulating water is extracted by the heat pump and used to heat the heating water in the heat pump, and then the heating water in the heat pump mixed with the heating water in the Heat Exchanger 1 and sent to the building for conventional heating that is integrated with heat pump heating or to the energy-storage tank for energy storage.

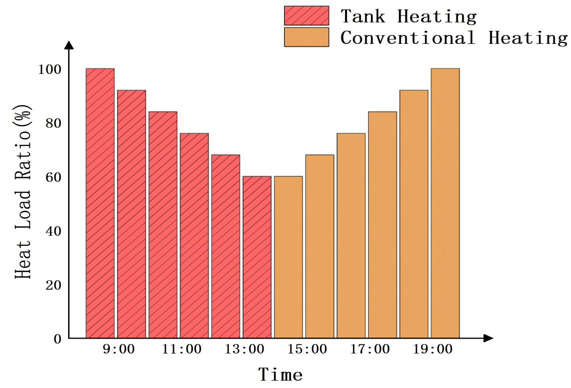

Fig. 2 Daytime heating operation mode

2.2 Heating operation model

The operation is divided into four stages in a day: (1) energy-storage in the water tank; (2) water tank heating; (3) conventional heating (integrated with heat pump heating); (4) no operation. In this paper, the energy-storage time is from 22:00pm to 6:00am; heating time is from 8:00am to 20:00pm.

The daytime heating operation mode is shown in Fig.2. In this mode, the energy-storage tank is used first for heating until the temperature of the tank drops to its lower limit and then the conventional heating

Table 1 Parameters used for optimization under 12 scenarios ("/" means: same as the values in scenario 1)

Scenario	Region	Energy-storage Tank Price (CNY/m^3)	Heat Pump Price (CNY/kW)	Heat Exchanger Price (CNY/m^2)	Water Pump Price (CNY/kW)	Lower-limit Temperature of the Tank (°C)
1 (basic scenario)	Xianxian Region	1000	1000	800	2000	40
2	/	/	/	2000	/	/
3	/	/	500	/	/	/
4	/	/	1500	/	/	/
5	Shanghai Region	/	/	/	/	/
6	/	/	/	/	1000	/
7	/	/	/	/	3000	/
8	/	500	/	/	/	/
9	/	1500	/	/	/	/
10	Tianjin Region	/	/	/	/	/
11	/	/	/	/	/	37
12	/	/	/	/	/	43

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Table 2 Time-of-use electricity prices of three regions (CNY/kW·h)

Time	Price Name	Xianxian Region	Shanghai Region	Tianjin Region
8:00-12:00; 16:00-20:00	Peak price	0.9304	1.11	1.2760
12:00-16:00	Flat price	0.6724	1.11	0.8305
22:00-6:00	Valley price	0.4144	0.527	0.4050

operation applies.

2.3 Model assumptions and constraints

In the system optimization, the following assumptions have been made:

(1) The supply water temperature (T10) for conventional heating is the same as the average of upper and lower limit temperatures of energy-storage tank (i.e. to maintain the same quality of heating) ;

(2) The outlet temperature of Heat Exchanger 1 (T2) in the conventional heating mode is the same as the averaged T2 in the water-tank energy storage mode;

(3) The difference between the inflow and outflow water temperatures for building heating is not more than 8°C;

(4) The geofluid temperature at the wellhead (T1) is 70°C; the reinjection geofluid temperature (T3) is: 13°C <T3<17°C (i.e. 15±2)°C; and T4=T8.

In this study, four decision variables (T_{max}, ε, ΔT_e, ΔT_{hp}) have been used for the optimization. They, together with their constraints, are described as follows:

(1) The upper limit of temperature of the energy-storage tank (T_{max}): ranging from 46°C to 55°C (subjects to heating temperature of the heat pump);

(2) The energy storage ratio (ε): ratio of the maximum heat-stored in the energy-storage tank to the average daily heating load of the design week, ranging from 0 to 1.

(3) End temperature difference at low temperature side of the Heat Exchanger 1 (ΔT_e=T2-T5): ranging from: 1°C to 7°C (subjects to the heat exchanger specification);

(4) Maximum temperature difference of the heat pump system (ΔT_{hp}=T8-T7): ranging from: 35°C-40°C (subjects to the heat pump specification).

3. SIMULATION RESULTS

3.1 Influence of energy storage ratio on LEC

12 scenarios have been investigated and shown in Table 1, and the first scenario is the basic scenario. The time-of-use electricity prices of the three regions listed in Table 1 are given in Table 2.

Fig.3 shows the effect of the change of energy storage ratio (ε) on the LEC of the system under three typical scenarios, while each of the other three decision variables takes its optimal value. It can be seen that there are step-drops of LEC in each scenario. Each of the steo-drop is caused by a step-decrease of a heat pump cost due to a shift from a higher capacity heat pump to a lower capacity one based on the hourly load calculation.

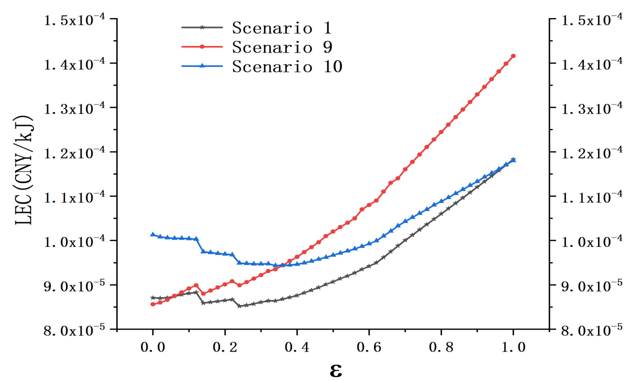

Fig. 3 Effect of the energy storage ratio (ε) on the LEC

In either scenario 1 or scenario 10 (Fig.3), the LEC decreases first and then increases as the energy storage ratio increases, whereas in scenario 9, the minimum value of LEC corresponds to energy storage ratio ε=0, meaning no energy storage is the best choice. In addition, in each of the three scenarios, the LEC of the system with a 100% storage ratio is higher than the LEC of the system without energy-storage, indicating that 100% use of energy-storage device for heating is not techno-economic.

3.2 Optimal values of decision variables in different scenarios

Fig.4 shows the optimal values of the 4 decision variables (T_{max}, ε, ΔT_e, and ΔT_{hp}) in each of the 12 scenarios shown in Table 1.

It is found that the optimal energy storage ratio was between 23% and 25% in most scenarios, while a

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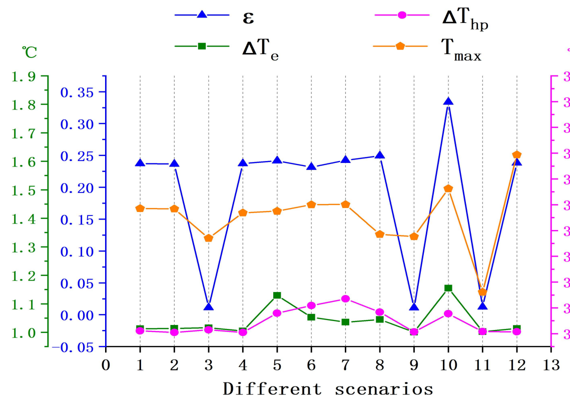

Fig. 4 Optimal values of decision variables (T_{max}, ε, ΔT_e, and ΔT_{hp}) in 12 scenarios

small number of scenarios showed that the system was either not suitable for the use of energy storage or that a larger storage tank should be used. At the same time, the influence of different factors on the optimal energy storage ratio can be found by comparing different scenarios. The comparison between scenario 3 and scenario 4 shows that the price change of heat pump has a great influence on the optimal energy storage ratio. The comparison between scenario 8 and scenario 9 indicates that changes in the price of energy-storage tanks also have a great impact on the optimal energy storage ratio. Too high price of an energy-storage tank will result in using the conventional heating mode without energy storage. The comparison between scenario 5 and scenario 10 shows that changes in peak-to-valley electricity prices have an obvious impact on the optimal energy storage ratio. The comparison between scenario 11 and scenario 12 indicates that changes in lower limit temperature of the energy-storage tank have an obvious influence on the optimal energy storage ratio. In addition, the comparison between scenario 1 and scenario 2 shows that the change in the price of the heat exchanger almost has no influence on the optimal energy storage ratio. The comparison between scenario 1, scenario 6 and scenario 7 indicates that changes in pump prices also have little influence on the optimal energy storage ratio.

The optimal value of T_{max} show the same trend as that of ε. When the energy storage tank is used, the values of T_{max} are almost all around 48°C.

The optimal values of the two decision variables, ΔT_e and ΔT_{hp}, are around 1°C and 35°C respectively in all scenarios.

3.3 Optimal LEC of each scenario

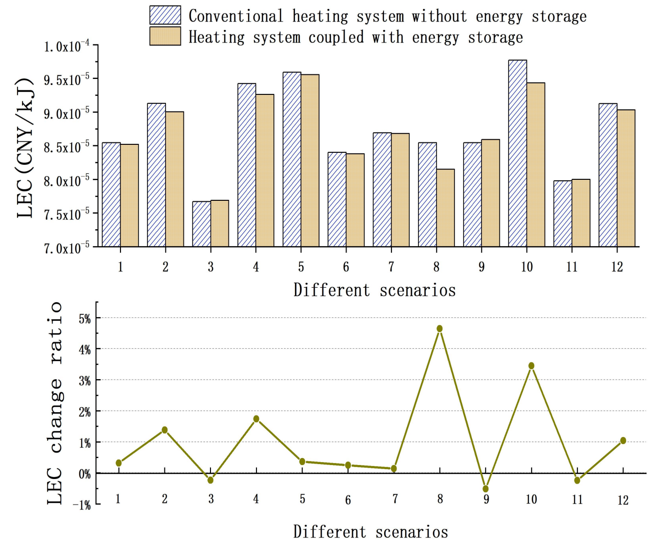

Fig. 5 Optimal LEC of each scenario – comparison between the conventional heating system and the heating system coupled with energy storage

Fig.5 is a comparison of energy storage-geothermal coupled heating systems with conventional geothermal heating systems (without energy storage) in different scenarios. The ordinate of the bar graph is the optimal LEC value, and the ordinate in the line graph represents the LEC change ratio. In scenario 8 and scenario 10, the LEC values for the coupled heating systems are obvious lower than those of the conventional geothermal heating systems, by 4.64% and 3.45%, respectively, indicating that using the energy storage has an advantage. In scenario 8, the lower cost of the energy storage tank resulted in a lower LEC. While in scenario 10, it is due to a significant difference in time-of-use electricity prices, which resulted in a significant reduction in operating costs. The advantage of using energy storage is less obvious in scenario 2, 4 and 12 when the heat exchanger cost, the heat pump cost and the lower limit temperature of the energy storage tank are high.

4. CONCLUSION

In this study, an optimization of a geothermal heating system coupled with energy storage for office building heating with consideration of time-of-use electricity prices has been carried out. 12 scenarios have been investigated. The main conclusions are as follows:

(1) The optimal energy storage ratio of the coupled system is between 23% and 25% in most scenarios.

(2) Energy-storage tank price, heat pump price, peak-valley electricity price difference and lower limit

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temperature of the energy-storage tank have great influence on the optimal energy storage ratio. Water pump price and heat exchanger price have little influence on the optimal energy storage ratio.

(3) The energy storage-geothermal coupled heating system has obvious advantages over the conventional (no energy storage) geothermal heating system in the following two scenarios: when the storage tank price is 500 CNY/m^3, the corresponding optimal energy storage ratio is 24.95%, with a 4.64% reduction in LEC; when the peak-to-valley electricity price ratio is 3.151, the corresponding optimal energy storage ratio is 33.38%, with a 3.45% reduction in LEC.

(4) Further research is necessary and is in progress to investigate more operation modes to have this energy storage-geothermal coupled heating system more techno-economic.

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