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Analysis on the Long-term Performance of a Large-scale Seasonal Borehole Thermal Energy Storage System

Fang Guo [1], Pengchao Li [1], Lili An [2], Xudong Yang [1*]

1 Department of Building Science, School of Architecture, Tsinghua University, Beijing 100084, China

2 The Third Primary School on Fulilu Road, Xigu District, Lanzhou City, Lanzhou 730000, China
(*Corresponding Author: xyang@tsinghua.edu.cn)

ABSTRACT

To obtain a better understanding of the characteristics of large-scale seasonal borehole thermal energy storage (BTES), a demonstration project was developed in Chifeng, China. In the project, combined heat sources of industrial waste heat and solar energy were adopted for 500000 m3 borehole thermal energy storage. In this study, the long-term thermal and economic performance of the demonstration project was analyzed based on the operation data of the demonstration project. First, actual system energy and economic performance of the demonstration project were analyzed. After that, a system simulation model was established and calibrated with the long-term system measured data from the demonstration project. The system simulation model was integrated into the LCCA model for assessing system long-term economic performance with different system design parameters and operation strategies. Then a multi-object optimization based on Non-dominated Sorting Genetic Algorithm II (NSGA-II) was conducted for finding the optimal design configuration and system performance.

The results of this study showed that, the annualized cost of borehole thermal energy storage of the studied system around 4-6 US$/GJ, and it could be further reduced to 2.7 $/GJ in China by reducing the borehole drilling cost and returning water temperature of the district heating network. Which emphasized that borehole thermal energy storage has a good application prospect in future urban distributed energy systems.

Keywords: borehole thermal energy storage, BTES, industrial waste heat, solar energy, district heating

NONMENCLATURE

Abbreviations

BTES	Borehole Thermal Energy Storage
HTF	Heat Transfer Fluid
IWH	Industrial Waste Heat
LCCA	life cycle cost analysis
NSGA-II	Non-dominated Sorting Genetic Algorithm II
SWH	Solar Water Heating
STES	Seasonal thermal energy storage

Symbols

1. INTRODUCTION

Seasonal thermal energy storage (STES) can significantly improve the efficiency of district heating systems based on sustainable energy[1]. STES allows abundant thermal energy generated during non-heating seasons to be effectively stored and used for building heating in winter, significantly increasing the year-round energy efficiency of heating systems. Additionally, STES can provide a powerful backup for short-term thermal energy storage when transient excess heat exceeds the capacity of short-term storage, improving the flexibility of energy generation and transmission[2].

Borehole thermal energy storage (BTES) is one of the most widely used seasonal thermal energy storage technology, due to its economic efficiency[3] and universal applicability[1,4].

To better understand the characteristics of large-scale seasonal borehole thermal energy storage (BTES), a demonstration project was established in Chifeng, China. The project used a combination of industrial

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waste heat and solar energy to store thermal energy in a 500,000 m^3 borehole field. This study analyzed the long-term thermal and economic performance of the demonstration project based on its operation data. The actual initial investment and operating costs of the project were obtained and a life cycle cost analysis (LCCA) model was developed for the BTES system. Next, a system simulation model was established and integrated into the LCCA model to assess the long-term economic performance of the system with different system design parameters and operating strategies. A multi-objective optimization based on Non-dominated Sorting Genetic Algorithm II (NSGA-II) was conducted to find the optimal design configuration and system performance.

2. SYSTEM DESCRIPTION

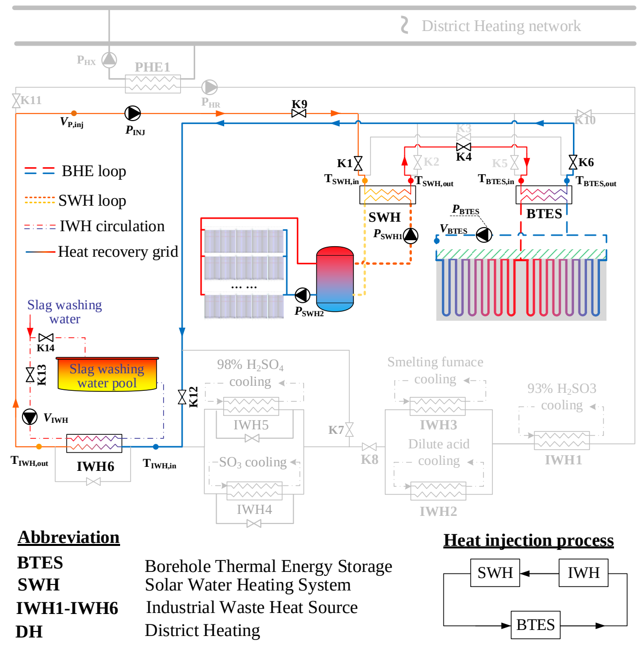
2.1 System description

The demonstration system studied in this paper is a large-scale seasonal borehole thermal energy storage (BTES) system located in Chifeng, China (geographical coordinates 42.28°N, 118.87°E). The system uses industrial waste heat (IWH) and solar energy as combined heat sources for seasonal thermal energy storage. The BTES-integrated heating plant was built near a local copper plant, where an IWH recovery system was installed. Different IWH sources with different temperature ranges and supply characteristics were integrated into a heat recovery network[5]. The newly built BTES system and solar water heating system were added to the original heat recovery network as subsystems. After the BTES system was built, a portion of IWH and solar energy was injected into the ground during non-heating seasons and extracted and supplied to the city's central heating network in winter.

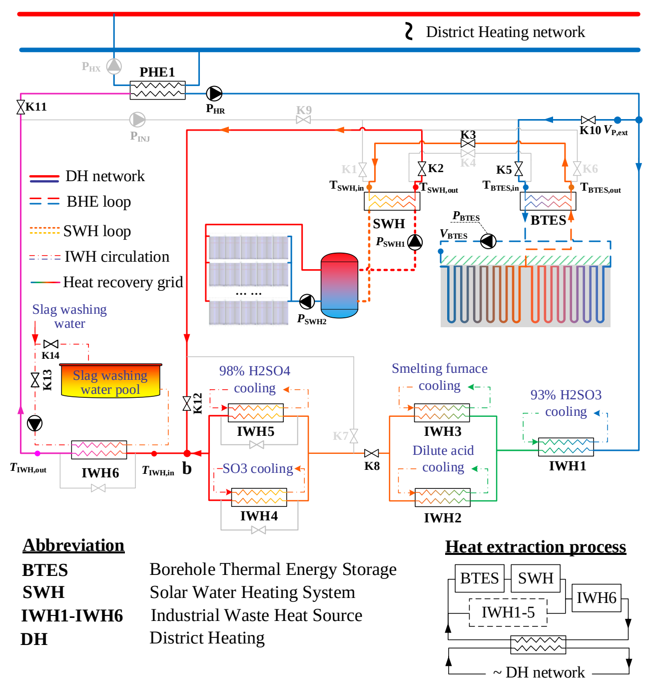
2.2 System scheme

A system diagram of the primary operation mode is illustrated in Fig. 1.

The industrial waste heat (IWH) recovery system consists of six individual IWH sources, labeled IWH1 to IWH6 in Figure 1. Heat sources IWH1 to IWH5 are the circulated cooling water of five individual industrial processes, and IWH6 is the slag-flushing water of a smelting furnace. These heat sources are integrated and connected as a parallel-series heat recovery network to transfer heat step-by-step to the heat transfer fluid (HTF) to increase the overall supply temperature. The newly built solar water heating system and BTES system are added to the original heat recovery network as subsystems, each with separate circuits and connected to the heat recovery network through plate heat exchangers.



(a)



(b)

Fig. 1. Schematic illustration of system process of a) heat injection and b) heat extraction.

A complete operating year is divided into a heat injection period and a heat extraction period, which overlap with the local non-heating season and heating season, respectively. During the heat injection period, IWH6 is selected as the primary heat source for seasonal thermal energy storage due to its high supply water temperature (around 70 °C) and stable dynamic supply. Additionally, IWH4 and IWH5 can be used as experimental heat sources and connected to the BTES by closing valve K12 and opening valve K7. Only one heat source can be selected for heat injection at a time. Once a heat source is connected to the BTES, the other heat sources are bypassed and switched to the cooling tower. The heat transfer fluid (HTF) is first heated by the IWH system and then further heated by the solar water heating system. The hot water then flows through the BTES system, injecting heat into the ground storage.

During the heat extraction period, the BTES system and solar water heating system are coupled with all the existing IWH sources to form a new heat recovery network. A portion of the low temperature return water of the heat recovery network is first distributed to the BTES system for heat extraction (from point a in Fig. 1b). Subsequently, the HTF passes through the solar water heating system. Then, the supply water of the solar water heating system mixes with the supply water of the IWH system (at point b in Fig. 1b) and passes through IWH6 to be further heated before transferring heat to the district heating network from plate heat exchanger PHE1.

The design return water temperature of the district heating network is approximately 20 °C. This low return water temperature will be made possible by the novel central heating planning of Chifeng, which is intended to increase the penetration of sustainable energy in the urban energy grid. The reduction of the return water temperature will be achieved by optimizing the topology of the heating network and utilizing absorption heat pumps at community heating stations.

2.3 BTES system

A total of 468 boreholes were constructed in the first phase of the project. The depth of the boreholes was 80 m.

The layout of the BTES is shown in Fig. 2. The borehole thermal energy storage (BTES) field consists of 468 boreholes arranged in a hexagonal shape with uniform spacing of 4 meters. To facilitate system monitoring, the boreholes are divided into six equilateral triangle-shaped subzones, each with 78 boreholes. Within each subzone, the boreholes are further divided into 13 branches, each with six boreholes connected in series by horizontal pipes.

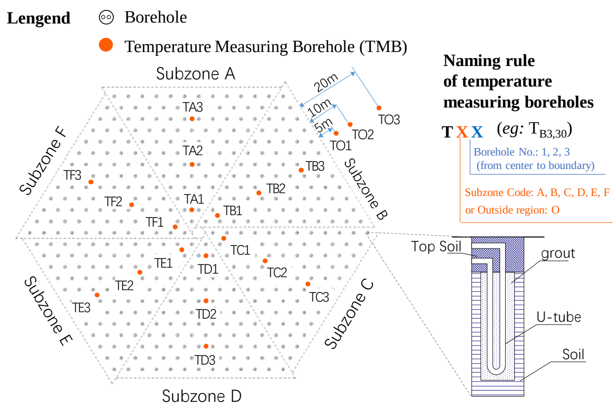


Fig. 2. Layout of the BTES and the temperature measuring boreholes[6].

3. METHODOLOGY

3.1 System monitoring

The demonstration system is equipped with an automated control system that enables online monitoring of the system operating parameters, the use of which allows for analyzing of system long-term thermal and economic performance.

The installation locations of the main measurement points are labelled in Fig.1 and shown in Table.1.

Table.1 system measurement points

Sensor	Item	Description
Temperature	$T_{BTES,in}$ / $T_{BTES,out}$	Inlet and outlet temperature of the BTES system
	$T_{SWH,in}$ / $T_{SWH,out}$	Inlet and outlet temperature of the SWH system
	$T_{IWH,in}$ / $T_{IWH,out}$	Inlet and outlet temperature of the IWH system
Volumetric Flow Rate	V_{BTES}	Volumetric flowrate of the BTES system
	V_{IWH}	Volumetric flowrate of the IWH system
	V_{SWH1}/V_{SWH2}	Volumetric flowrate of the SWH system (primary and secondary side respectively)
Pump Power	P_{BTES}	Power rate of circulation pump of BTES system
	P_{SWH1}/P_{SWH2}	Power rate of circulation pump of SWH system (primary and secondary side respectively)
	P_{IWH}	Power rate of circulation pump of IWH system
	P_{INJ}	Power rate of circulation pump of the hear injection network in heat injection period
	P_{HR}	Power rate of circulation pump of heat recovery network in heat extraction period

3.2 System simulation

The actual running time of the demonstration project was about 1.5 years, after which the system was discontinued due to the relocation of the copper plant. Therefore, the subsequent operation of the system was simulated using the TRNSYS platform. Component models were selected from the libraries and enhanced by the manufacturing data and long-term monitoring results from the real system in Chifeng. The ten-year long cycle operation of the system was simulated to obtain the operating parameters of the system in the quasi-steady state cycle to perform a full life cycle analysis of the system.

A schematic diagram of the system model, showing the connections between the main components, is shown in Fig. 3.

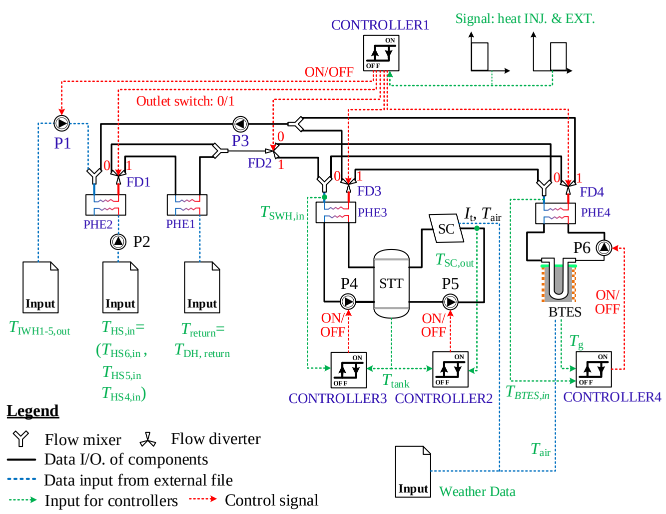


Fig. 3. Diagram of system model based on TRNSYS platform

3.3 Performance evaluation

The system performance were evaluated using the following metrics.

3.3.1 Energy performance evaluation

The annual heat injection and extraction of BTES were calculated as follows:

$$Q_{\mathrm{IN}} = \sum_{i=n_{\mathrm{s,in}}}^{n_{\mathrm{e,in}}} (\dot{m}c)_{\mathrm{HTF}} \cdot \left[T_{\mathrm{BTES,in}}(i) - T_{\mathrm{BTES,out}}(i)\right] \cdot \Delta\tau \quad (1)$$

$$Q_{\mathrm{EX}} = \sum_{i=n_{\mathrm{s,ex}}}^{n_{\mathrm{e,ex}}} (\dot{m}c)_{\mathrm{HTF}} \cdot \left[T_{\mathrm{BTES,out}}(i) - T_{\mathrm{BTES,in}}(i)\right] \cdot \Delta\tau \quad (2)$$

Here, Q_{IN} and Q_{EX} indicate total heat injection and heat extraction in one complete operation cycle, respectively. $n_{\mathrm{s,in}}$ and $n_{\mathrm{e,in}}$ represent the number of the start and end hours of the heat injection period, respectively, $n_{\mathrm{s,ex}}$ and $n_{\mathrm{e,ex}}$ represent the number of the start and end hours of the heat extraction period, respectively. $(\dot{m}c)_{\mathrm{HTP}}$ represent the heat capacity flow rate of the heat transfer fluid (in W/K). $\Delta\tau$ is the simulation time step (in s).

The cyclic energy efficiency of BTES is the most widely adopted metric for thermal performance evaluation[7-9] . Usually, it is defined as the heat

Table 2. Properties and parameters of system components

Component	Item	Value
***Solar collector* (SC)**	Collector type	Vacuum tube collectors
	Module	Type 71
	Aperture area of a single collector	3.67 m^2
	Tilted angle	55°
	Collector connection	6 per series, totaling 46 branches
	Collector efficiency	η=0.497-1.483T_i*
BTES	Module	Type 557a
	Number of radical regions	6
	Number of vertical regions	10
	Reference borehole flowrate	769 kg/h
	Pipe to pipe heat transfer	-1
	Fluid specific heat	4.2 kJ/kg·K
	Fluid density	983.4 kg/m^3
	Fraction of storage height insulated	0
	Header depth	2 m
	Number of preheating years	0
	Initial surface temperature of storage volume	10 ℃
	Insulation thickness on the top and sides of storage	0
	Total borehole count	468
	Borehole height	80 m
	Borehole connection	6 series-connected boreholes in one branch, 78 branches connected in parallel
	Buried pipe	Single-U
	Inner/outer diameter of the buried pipes	23.2 mm / 32.0 mm
	Borehole spacing	4 m
	Heat transfer fluid	Water
	Top layer height	2 m
	Soil thermal conductivity	1.2 W/(m·k)
	Specific heat capacity of soil	2612 kJ/m^3·k
Short-term storage tank	Module	Type 60
（SST）	Storage volume	1000 L
	Height	2 m
	Diameter	0.8 m
	Heat loss coefficient	0.4 W/(m^2·K)
	Auxiliary heater	None
Pump	Module	Type 114
	Output	P1: Q = 1200m^3/h, H = 80m, 800kW
		P2: Q = 220 m^3/h, H = 40m, 22kW
		P3: Q = 60m^3/h, H = 80m, 18kW
		P4: Q = 60m^3/h, H = 25m, 15kW
		P5: Q = 60m^3/h, H = 10m, 7.5kW
Controller	Module	Type 2b
Plate heat exchanger	Module No.	Type 5b
	Type	Counter flow heat exchanger
	Heat transfer coefficient	PHE1: 896 W/(m^2·K)
		PHE2: 896 W/(m^2·K)
		PHE3: 486 W/(m^2·K)
		PHE4: 896 W/(m^2·K)
External data reader	Module	Type 9a

recovery ratio of the energy extraction to the energy injection of the BTES for a complete operation cycle, which is given as

$$\eta_{EN} = \frac{Q_{EX}}{Q_{IN}} \tag{3}$$

The component modules and main parameters adopted are listed in Table 2.

*Here, $T_i = (T_{in} - T_{amb}) / I_t$, where T_{in} is the inlet temperature of the collectors (in K), T_{amb} is the environmental temperature (in K), and I_t is the total incident radiation on the tilt surface of the collectors (in W/K).

3.3.2 Economic performance metrics

The total annualized cost (TAC) of the BTES system includes the incremental cost of building and operating the system, excluding the cost of the IWH recovery system, which have already been put into operation.

$$\begin{aligned}\mathrm{TAC}=&(N_b H_b C_b)\mathrm{CRF}_b+(V_b C_a)\mathrm{CRF}_a+C_{co}\mathrm{CRF}_{co}\\&+\sum_{i=1}^{m}\left[(C_p P_p)_i \mathrm{CRF}_p\right]+C_{op}+C_m\end{aligned} \tag{4}$$

Where N_b is the total number of boreholes; H_b (in m) is the total height of boreholes; C_b (in US$/m) is the unit cost of boreholes (including the drilling cost and installation cost); V_b (in m^3/h) is the circulation flow rate of the BTES system; C_a (in US$$\cdot m^{-3}\cdot h$) is the unit cost for the accessory pipelines and devices of the BTES system; C_{co} (in US$) is the initial cost of the control system of the BTES system; C_p (in US$/kW) is the unit cost of circulation pump; P_p (in kW) is the power of the circulation pump; m represents the total number of pumps in the BTES system; C_{op} (in US$) is the annual operation cost of the system; C_{om} (in US$) is the annual maintenance cost; CRF represents the capital recovery factor for different items of system cost, which was calculate as:

$$\mathrm{CRF} = \frac{r(1+r)^n}{(1+r)^n - 1} \tag{5}$$

where r is the discount rate; n (year) is the length of life cycle of system components.

3.4 System optimization

The main goal of the system design for the demonstration project is to provide greater flexibility in system operation to test a wider range of system operating parameters, system integration methods, control strategies, etc. Therefore, the system design of the demonstration project is not primarily based on economic considerations.

A multi-objective optimization was conducted to identify the boundaries of the energy performance and the economic benefits of the studied system scheme. The total number of boreholes and circulation flow rate of the BTES were set as the optimizing variables, and the total annualized cost (TAC) and total heat supply from the BTES were selected as the objective functions for the optimization.

The optimization was carried out by an external optimizer using the Multi-Objective Building Optimisation (MOBO) tool with the Non-dominated Sorting Genetic Algorithm II (NSGA-II).

4. RESULTS AND DISCUSSION

4.1 System monitoring results

4.1.1 Heat injection period

Fig. 4 shows the long-term temperature variations of the BTES system's inlet and outlet water, as well as the ground temperature, averaged daily. The shadows around each curve indicate the daily ranges of the measured temperatures. The temperature at 40 meters depth in subzone B represents the temperature variation of the BTES. The mean inlet and outlet temperatures for different operation phases are shown at the bottom of the figure.

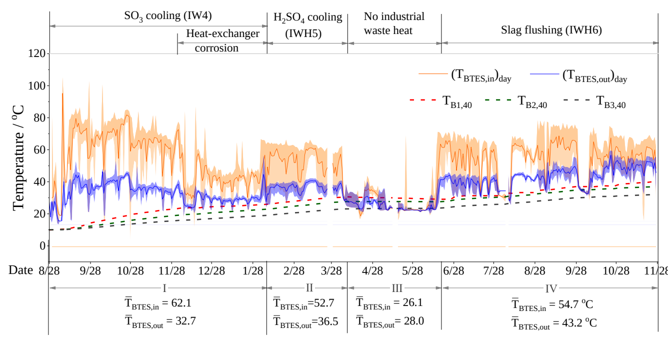


Fig. 4. Long-term monitoring results for the inlet, outlet, and soil temperatures of the BTES system, where $T_{BTES,in}$ and $T_{BTES,out}$ represent the inlet and outlet temperatures of the BTES system, respectively, and $T_{B1,40}$, $T_{B2,40}$, and $T_{B3,40}$ represent the soil temperatures measured from temperature measuring boreholes in subzone B (the naming rule for the temperature sensors is presented in Fig. 2).

The BTES system exhibited a large thermal inertia. Affected by the instabilities of industrial processes and solar energy, the inlet temperature to the BTES exhibited significant fluctuations over time. The ground temperature remained stable and increased slowly with the heat injection. The daily variation of the measured ground temperatures was <0.1 °C throughout the entire preheating period.

As indicated by the long-term performance of the BTES, the daily average outlet temperature fluctuated with the fluctuation of the daily average inlet temperature. The difference between the inlet and outlet temperatures tended to decrease with the increasing ground temperature.

4.1.2 heat extraction period

Due to the relocation of the copper plant, the demonstration project has not yet realized heat extraction operation. While for system debugging, a one-month trail heat extraction operation was carried out after the first preheating period. Fig. 5 shows the temperature variations of the BTES system's inlet and outlet water, as well as the ground temperature in this period, averaged daily. The shadows around each curve indicate the daily ranges of the measured temperatures.

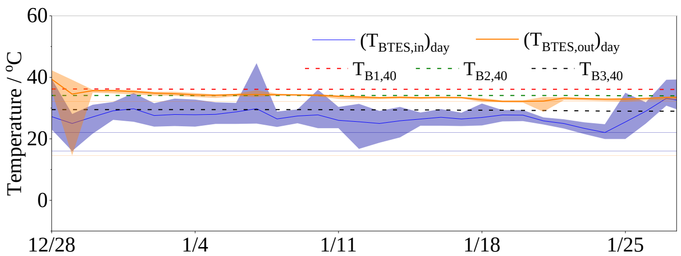


Fig. 5. Monitoring results for the inlet, outlet, and soil temperatures of the BTES system in the trial heat extraction period, where $T_{BTES,in}$ and $T_{BTES,out}$ represent the inlet and outlet temperatures of the BTES system, respectively, and $T_{B1,40}$, $T_{B2,40}$, and $T_{B3,40}$ represent the soil temperatures measured from temperature measuring boreholes in subzone B (the naming rule for the temperature sensors is presented in Fig. 2).

4.2 long-term simulation results

Fig. 6. shows the long-term temperature variation of the ground at a depth of 40 m for the BTES, generated from system simulation. After three years of intentional pre-heating and periodic heat injection and extraction, the BTES reaches a quasi-steady state, with the ground temperature gradually departing from its initial state and achieving a new, periodically heat-balanced state. The ground temperature at each position in the BTES fluctuates regularly around its heat-balanced temperature. The temperature stratification from the center to the boundary of the BTES forms during the pre-heating period and remains stable during the following simulation years. During a quasi-steady state operation cycle, the highest and lowest temperatures at the center of the BTES ($T_{1,40}$) are approximately 57 and 45 °C, respectively.

The simulation results of TO1 (5 m from the BTES boundary), TO2 (10 m), and TO3 (20 m) show the temperature variation of the BTES surrounding region. Unlike the BTES interior temperature, the BTES exterior temperature increased continuously during the heat injection and extraction periods, indicating that heat dissipation 5 m away from the BTES is irreversible.

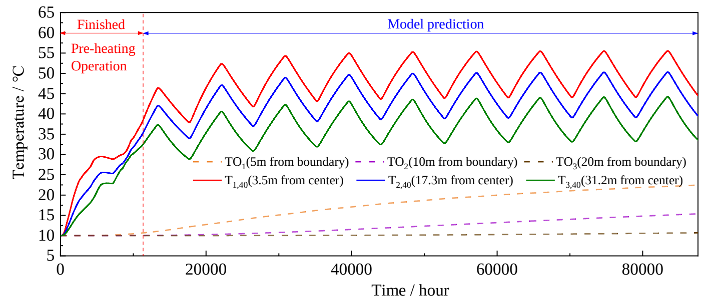


Fig. 6. Predicted variation of ground temperature over 10 years.

The prediction of annual heat injection, heat extraction, heat loss, and thermal energy efficiency of the BTES is shown in Fig. 7. A total of 1.96×10^5 GJ of heat was injected into the BTES for the first ten years. A total of 1.26×10^5 GJ of the total heat injection was extracted and supplied to the district heating network, 3.31×10^4 GJ was dissipated to the environment. With continuous system operation, the annual heat injection, extraction, and energy efficiency of BTES gradually tend to be stable. In the 10th year, the year-round energy efficiency of BTES was 83.12%.

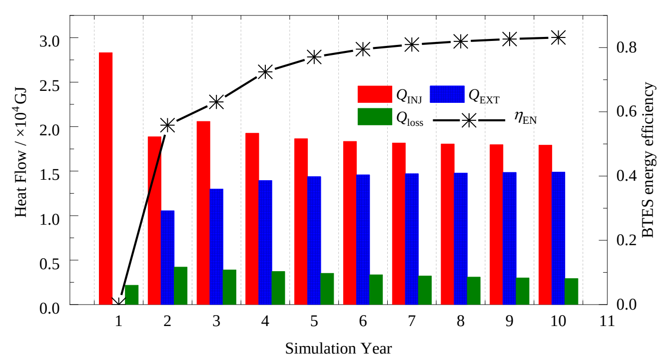


Fig. 7. Prediction of the annual energy performance of the studied system.

4.3 system optimization

The results of the system optimization are shown in Fig. 8. Since the cost of borehole drilling varies greatly with the geological structure, this paper calculates the system optimization results for three different borehole drilling cost conditions. The three solid lines in the Fig.8 represent the Pareto frontiers under three different drilling costs, respectively. For the demonstration project, the drilling cost for unit length is 13.27 US$/m. The total annualized cost for unit extraction was around 4-6 US$/GJ. Currently, in areas with good geological conditions, drilling costs can be reduced up to around 4.7 US$/m in China, thus the total annualized cost for unit extraction can be reduced to around 3-4 US$/GJ.

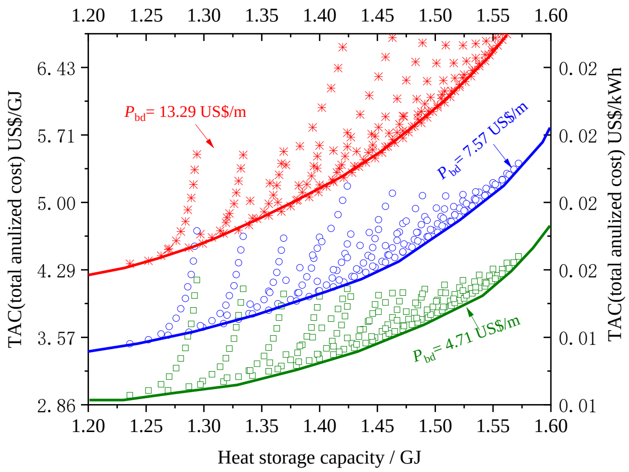


Fig. 8. Optimization results under three different drilling costs.

The return water temperature to the BTES will significantly affect the system's heat extraction. Using heat pump further reducing the return water temperature of the BTES, can effectively reduce the annualized cost of the system. As shown in figure 8, the total annualized cost of the system could be reduced to 2.7 $/GJ with 10°C return water temperature to the BTES.

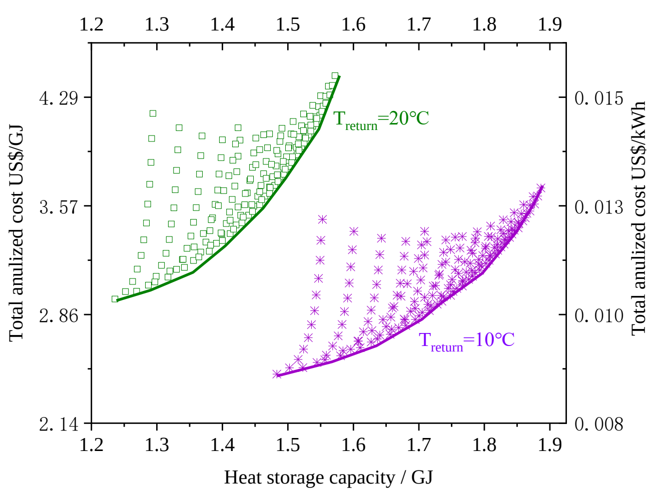


Fig. 9. Optimization results under two different return temperature.

5. CONCLUSIONS

In this study, a demonstration project of large-scale seasonal borehole thermal energy storage (BTES) developed in Chifeng, China was studied. The long-term thermal and economic performance of the demonstration project was analyzed based on system monitoring and simulation. First, a life cycle cost analysis (LCCA) model was built for borehole thermal energy storage system. After that, a system simulation model was established and calibrated with the long-term system measured data from the demonstration project. After that a multi-object optimization based Non-dominated Sorting Genetic Algorithm II (NSGA-II) was conducted for finding the optimal design configuration and system performance.

The system monitoring results showed that large-scale seasonal borehole thermal energy storage (BTES) has a strong ability to buffer against short-term temperature fluctuations in industrial waste heat (IWH) sources and district heating networks. This is beneficial for improving the stability of district heating and IWH recovery. The initial heat balance of the LSSBTES is gradually established within 3-4 heat injection-extraction cycles, and the annual energy input and output of the storage gradually reach stability.

The results of this study showed the annualized cost of borehole thermal energy storage of the studied system was 6.3 $/GJ, and it could be further reduced to 2.7 $/GJ in China by reducing the returning water temperature of the district heating network. Which emphasized that borehole thermal energy storage has a good application prospect in future urban distributed energy systems.

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DECLARATION OF INTEREST STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. All authors read and approved the final manuscript.

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