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Economic Assessment of Deep Single-Well Geothermal Systems and Conventional Alternatives for Building Heating in North China

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ABSTRACT

The main modes of direct geothermal utilization include double-well (or multi-well) reinjection systems, deep single-well systems (both open-loop and closed-loop), and shallow ground source heat pump systems with buried pipes. These geothermal heating modes offer notable advantages such as high energy efficiency, operational stability, and environmental sustainability. Based on the geothermal resources and building heating demand in North China, this study selects representative geothermal heating modes-including double-well reinjection, deep open-loop single well system, deep closed-loop single well system, shallow buried pipe systems, for a techno-economic comparison using natural gas boilers as a reference. Evaluation metrics include life cycle cost (LCC), annual energy cost (AEC), and payback period (PP). Combining field tests with numerical simulations, the study further compares the economic performance of the deep open-loop single-well system with a gas boiler peaking system under a cascading utilization model. Results show that the deep open-loop system becomes more economical than gas boilers starting in the ninth year (without considering energy price fluctuations) or the sixth year (when fluctuations are considered), while the double-well reinjection system outperforms gas boilers by the fourth year. The findings align well with actual project data and provide both theoretical support and practical guidance for the selection and optimization of clean heating systems.

1 INTRODUCTION

Geothermal energy, as a clean, sustainable, and stable heat source, has become an important pathway for promoting low-carbon and green transitions in the building sector (Wang et al., 2020). By the end of 2021, China's total geothermal heating area had reached approximately 1.39 billion m^2, of which shallow geothermal systems accounted for about 840 million m^2. Different geothermal systems vary significantly in geological suitability, economic performance, and operational stability, which has become a key factor limiting large-scale deployment.

Shallow borehole heat exchanger (BHE) heat pump systems generally exhibit higher coefficients of performance (COP) than air-source heat pumps; however, improper design or operation may lead to seasonal thermal imbalances in certain regions, compromising long-term sustainability (Dai et al., 2019). Deep doublet-well (DW) systems can directly exploit hydrothermal resources, but their application is constrained by the high cost of drilling and the difficulty or poor economics of reinjection in some sandstone formations, resulting in both policy and economic limitations in engineering practice (NEA. 2021). Deep closed-loop borehole systems (DBHE) have been implemented in some projects in recent years, yet their heat extraction capacity is limited and exhibits pronounced decline over time.

To address these challenges, Dai et al. proposed a novel deep open-loop single-well system (DOLGW) in 2019 and conducted a field test in 2021 in a sandstone geothermal well in Tangshan, Hebei Province, China, with a depth of 1400 m and a bottom temperature of approximately 65 °C. The results showed that the heat extraction rate per unit well depth exceeded 350 W/m, significantly outperforming closed-loop systems under similar geological conditions and offering a new technical pathway for deep geothermal development (Lei et al., 2023).

Although the aforementioned geothermal heating technologies have been applied in various regions, their geological applicability, capital investment, operational economics, and responsiveness to user demand differ substantially. Therefore, conducting a systematic techno-economic assessment of multiple geothermal heating modes is essential for guiding the selection of optimization of regional energy structures. This study evaluates four representative geothermal heating modes-shallow BHE systems, deep DW systems, deep DBHE systems, and deep DCOP systems-from the perspectives of system investment, operating cost, and user demand, with the aim of supporting technology selection and the broader deployment of deep geothermal heating systems.

Several studies have examined the techno-economic performance of geothermal heating modes. For example, Envelope et al. employed the Levelized Cost of Heat (LCOH) method to analyze deep doublet-well (DW) systems, evaluating the influence of well spacing, drilling costs, hydrothermal reservoir permeability, and reinjection temperature on system design and operational optimization. Thomasson and Rinat (2022) assessed the economic performance of closed-loop DBHE systems for a 7,874 m^2 building in Espoo, Finland, and demonstrated that increasing borehole depth improves heat pump COP and reduces annual operating costs. Based on annual total cost and LCOH analyses, they further proposed optimized design and operational strategies. Li [8] investigated the operating costs and payback period of shallow BHE systems and compared them with conventional gas boiler heating.

Overall, existing techno-economic analyses have predominantly focused on a single geothermal heating mode, most previous studies were conducted on small-scale buildings-typically below 10,000 m^2, and in some cases only a few hundred square meters. To address these gaps, this study conducts a comparative techno-economic assessment of multiple geothermal heating modes for a representative medium-scale district heating project (30,000 m^2). The analysis incorporates typical geothermal engineering cases in China, relevant national and local standards, energy prices, and operation–maintenance practices, using gas boiler (GB) heating as a reference. The findings provide theoretical guidance for the geothermal engineering application.

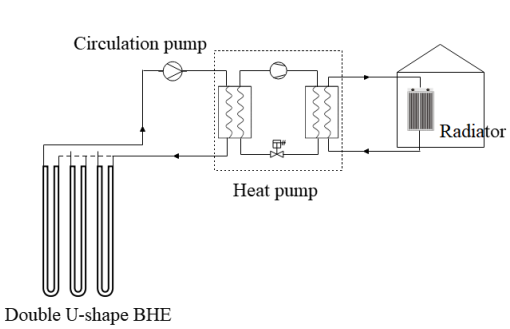
2 TYPICAL GEOTHERMAL HEATING MODES AND ECONOMIC EVALUATION METHODS

2.1 Representative Building Scale

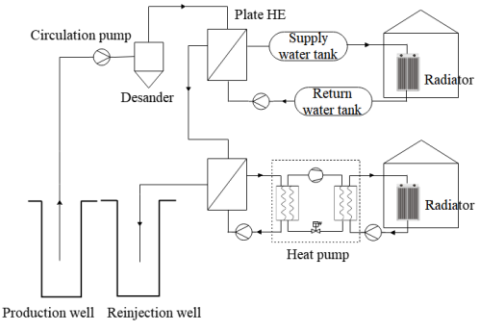
This study conducts a techno-economic assessment of several typical geothermal heating modes using the atmospheric conditions, geothermal resource characteristics, and building heating standards of northern China as the reference baseline. Field test results indicate that the deep open-loop single-well circulation system (DOLGW) can achieve a heat extraction capacity of 500-2000 kW [Cai, 2019], which is sufficient to meet the heating demand of buildings with areas of 30,000–50,000 m^2 in northern China. In practice, each heat source technology has its suitable service scale: deep doublet-well (DW) systems and gas boilers are applicable to large-scale heating of 0.1-1.0 million m^2; shallow BHE systems are generally suitable for small-scale loads of around 100 m^2; and deep closed-loop boreholes (DBHE) typically serve areas of approximately 10,000-15,000 m^2. Accordingly, this study prioritizes engineering case data with similar heating scales, or adopts the average heating cost corresponding to this scale.

2.2 Typical Geothermal Heating Modes

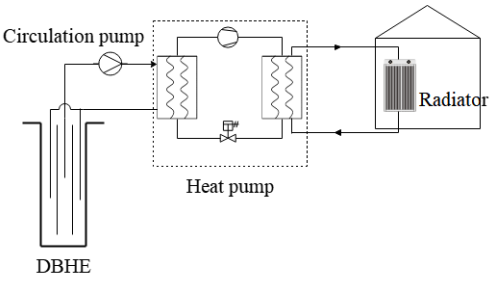
Figure 1 illustrates the typical geothermal heating systems considered in this study. Figure 1(a) shows the shallow borehole heat exchanger (SBHE) system, consisting mainly of underground heat exchanger loops, heat pump units, and terminal heating devices. Figure 1(b) depicts the deep doublet-well (DW) system, in which the need for a heat pump depends on the geothermal water temperature and the building heat load. When the geothermal supply temperature is sufficiently high, the heat pump can be omitted to improve overall economic performance. Figures 1(c) and 1(d) represent deep closed-loop (DBHE) and deep open-loop single-well circulation (DOLGW) systems, respectively. For comparison purposes, the conventional gas boiler (GB) system shown in Figure 1(e) is also included.



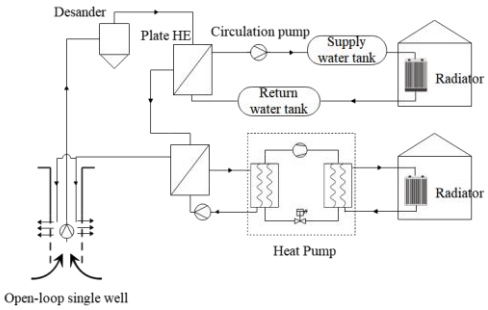
(a) SBHE system



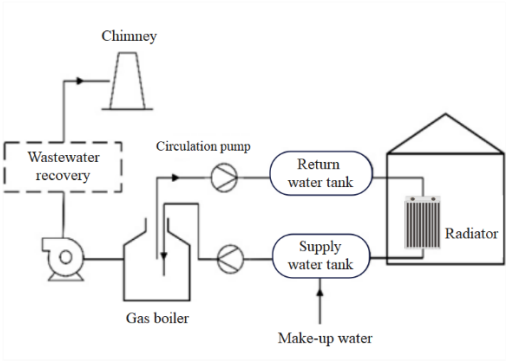
(b) DW system



(c) DBHE system



(d) DOLGW system



(e) GB System

Fig.1 Schematic of different heating system

2.3 Key Design and Operating Parameters

According to relevant design standards, the heating load for residential buildings ranges from 40 to 60 W/m^2, and a value of 45 W/m^2 is adopted in this study. The cooling load for commercial office buildings ranges from 80 to 110 W/m^2, and a value of 80 W/m^2 is selected. For the geothermal heating modes considered-doublet-well reinjection (DW), deep closed-loop single-well (DBHE), and shallow borehole heat exchanger (BHE) systems-typical engineering projects are available; therefore, the parameter values used in this study are sourced from representative case studies. The key design and operating parameters are summarized in Table 1.

Table 1 Parameters of different geothermal heating modes

Heating mode	Geothermal water outlet temperature (°C)	Outlet flow rate (t·h^{-1})	Reinjection temperature (°C)
DW	85	90	14
DBHE	26.1	28	9
SBHE (winter)	10.99	80	6.64
SBHE (summer)	27.0	80	32.0

3 DESIGN OF HEATING SYSTEMS AND ECONOMIC ANALYSIS METHOD

3.1 System Design of Typical Geothermal Heating Modes

Based on the design parameters specified in GB50019-2003 Design Code for Heating, Ventilation and Air Conditioning, , the outdoor design temperature for Tianjin is taken as -9°C.

3.1.1 Deep Open-Loop Single-Well System (DOLGW)

For a representative well depth of 2000 m, the reinjection flow rate is set at 60 t/h with a reinjection temperature of 8°C, and the ground surface temperature is assumed to be 15°C. The geothermal gradient in Tianjin typically ranges from 2.5 to 3.5°C per 100 m; a value of 2.8°C per 100 m is adopted in this study, yielding a bottom-hole temperature of approximately 71°C. Calculations show that the production temperature ranges from 35 to 50°C, corresponding to a single-well heat extraction capacity of 1437.3–1701.9 kW, sufficient to supply a heating area of 31,900-37,800 m^2. Using the Newton iteration method, the formula for determining the steady-state heating capacity is expressed as follows:

$$Q_{n+1} = Q_n - \frac{Q_n - 11.27W + 0.329W\theta}{1 + 0.329W[(\frac{1}{1+\beta})(\frac{Q_n+W}{A_t\alpha})^{\frac{-\beta}{1+\beta}} + \frac{1}{C_q V} + \frac{(\frac{S}{G_h} - \frac{1}{G_e})}{C_p(S-1)} - \frac{1}{2C_p G_e}]} \quad (1)$$

Where Q is the heat extraction capacity of the single well; W is the input power of the heat pump motor; θ denotes the average temperature difference across the condenser and evaporator of the heat pump; V is the building volume; S is a parameter associated with the design of the plate heat exchanger.

3.1.2 Deep Closed-Loop Single-Well System (DOLGW)

Based on the DBJ61/T 166-2020 Technical Code for Application of Deep Geothermal Borehole Heating Systems, the heat extraction of adeep closed-loop single well can be calculated as:

$$Q_i = (17.61 \times T \times k_a + 49.2 \times T - 2.23 \times k_a)\frac{H}{1000} - 8.63 \times T \times k_a - 61.93 \times T - 7.92 \quad (2)$$

Where Q_i is the heat extraction capacity of the closed-loop single well (kW); ka is the thermal conductivity of the surrounding formation (W/(m·℃); T is the geothermal gradient (℃/100 m); H is the drilling depth (m).

Using this equation, the heat extraction capacity of a closed-loop single well with a drilling depth of 2000 m is approximately 280 kW.

3.1.3 Shallow Borehole Heat Exchanger (BHE) System

In practical engineering applications, shallow geothermal systems typically adopt parallel double-U borehole configurations. The recommended linear heat extraction rates are 39-45 W/m in winter and 55-62 W/m in summer. Accordingly, this study adopts 42 W/m for winter and 58 W/m for summer. Based on Eq. (3), the heat extraction capacity of the BHE system is calculated as:

$$Q = \frac{NLq_L}{4000} \quad (3)$$

Where Q is the heat extraction capacity; N is the number of boreholes; L is the borehole depth; q_L is the unit-depth heat extraction rate.

Table 2 summarizes the design parameters, steady-state heat extraction capacities, and corresponding heating scales of the four typical geothermal heating modes.

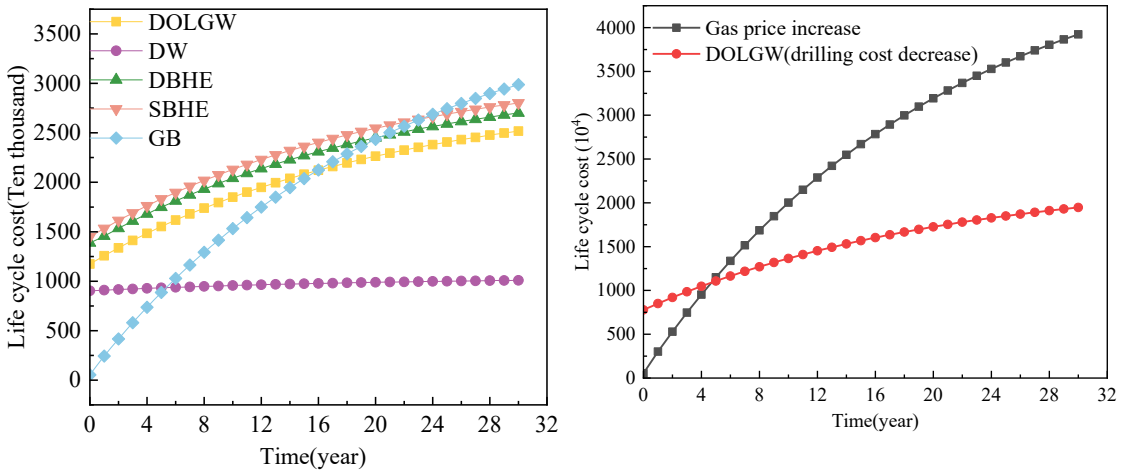
Table 2 Well depth, heat extraction capacity, and heating scale of different heating modes

Heating mode	Well depth / number of boreholes (m / –)	Heat extraction rate (kW)	Heating scale (10^4 m^2)
DOLGW	2000 / 1	1600	3.56
DW	2700 / 2	8296	15.46
DBHE	2000 / 5	1400	3.11
SBHE, winter	120 / 500	630	1.40
SBHE, summer	120 / 500	870	1.93

3.2 Life-Cycle Cost (LCC) Analysis

This study evaluates the 30-year life-cycle cost (LCC) of four geothermal heating modes and the gas boiler system, as illustrated in Fig. 5. The results show that the LCC of the gas boiler system increases rapidly over time due to its relatively high annual operating cost. In contrast, the open-loop single-well system exhibits a significantly lower LCC than the deep closed-loop single-well system, indicating superior economic performance. When compared with the gas boiler, the open-loop system becomes economically favorable after approximately nine years of operation.

It should be noted that the price parameters used in this study are not assumed constant but reflect potential future market and technological trends. In the foreseeable future, natural gas prices are likely to increase, while drilling costs are expected to decline. Under a scenario where natural gas prices rise by 40% (to 4.08 CNY/m^3) and drilling costs decrease by 20% (to 1197 CNY/m), the open-loop single-well system surpasses the gas boiler in economic performance as early as the sixth year of operation.



(a) Price fluctuation not considered (b) Price fluctuation considered

Figure 5. Comparison of Life Cycle Cost for different heating modes during 30-year period

4 CONCLUSIONS

This study evaluated the economic performance of four representative geothermal heating modes—deep open-loop single-well systems, doublet-well systems, deep closed-loop single-well systems, and shallow BHE systems-and compared them with conventional gas boiler heating for medium-scale buildings (30,000-50,000 m^2) in northern China. Based on a 30-year life-cycle cost (LCC) assessment, the gas boiler system exhibits a substantially increasing LCC due to its high annual operating cost. The deep open-loop single-well system becomes more economical than the gas boiler after approximately nine years of operation, while the doublet-well system shows an economic advantage as early as the fourth year. When future trends such as decreasing drilling costs and increasing natural gas prices are considered, the deep open-loop single-well system achieves economic superiority over the gas boiler system by the sixth year.

Acknowledgements

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