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Design and Key Points Analysis of the Intermediate-depth Geothermal Central Heating Project in Pingyuan County

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Abstract:
In the past 20 years, In China deep geothermal heating projects have developed rapidly, in the scale of the world top. It is understood that Iceland can provide central heating for 90% of homes by developing medium-and deep-seated geothermal reservoirs. Germany has gradually made medium-and deep-seated geothermal reservoirs a key target for development, to meet the heating needs of Germany 1/4. Based on the actual engineering project, this paper analyzes the geothermal state, key technology, core parameters and so on in the project engineering design, and compares and selects the schemes in the design, finally, the optimal design scheme is determined and the economic benefit is analyzed. The key problems in engineering design are summarized and some suggestions are put forward.

Keywords: intermediate-depth geothermal; intermediary water; cascading utilization; geothermal heating.

INTRODUCTION

Both nationally and provincially, various measures have been implemented to promote the development of intermediate-depth geothermal utilization. Provinces such as Beijing and Shanxi have also established local standards for intermediate-depth geothermal exploration and design to advance survey and design efforts for such projects. With the gradual formulation of provincial energy policies, planning, and strategies for achieving carbon peak targets, significant progress has been made in the development and utilization of geothermal resources compared to previous years.

The western urban area of Ping yuan County previously relied on waste heat from the Yangmei Power Plant for centralized heating. Due to improper operation the Yangmei Power Plant is scheduled to shut down in 2024. Consequently, the existing centralized heating system in the western urban area requires a sustainable alternative heat source compliant with national industrial and environmental policies. During the 14th Five-Year Plan, there has been significant national emphasis on promoting renewable energy utilization. Shandong Province has implemented various policy measures, such as financial subsidies, electricity price discounts, and tax incentives, to promote the adoption of intermediate-depth geothermal energy. Therefore, this study introduces intermediate-depth geothermal energy as the primary heat source to meet the heating demands of a 2.02 million square meter building area in the western urban area of Pingyuan County, with coal-fired boilers from the Yangmei Power Plant as backup heat sources. The project utilizes 'heat extraction without water consumption' technology, implementing multi-stage utilization of intermediary water after groundwater extraction to minimize reinjected water temperatures and maximize temperature differentials for efficient geothermal water usage. This paper presents an analysis of the impact of extraction well and reinjection well spacing on temperature differentials, using data from experimental wells to determine optimal configurations. Through the comparison and analysis, it is determined that the optimal distance between water intake and recharge wells in this project should be 400m, the groundwater should be fully utilized and the temperature of recharge water should not be higher than 20 ° C, the intermediate water temperature should be determined according to the difference between the source side water temperature and the primary water temperature to realize the cascade utilization of groundwater and improve the energy efficiency of the water source heat pump unit, so as to improve the heating capacity of the well [1-3].

PARAMETERS DETERMINATION FOR GEOTHERMAL WELLS

Types of Geothermal Resources and Utilization Forms

Geothermal energy refers to the heat energy contained within the earth's subsurface rocks, fluids, and magma, which can be developed and utilized by humans. Geothermal systems are categorized into five types based on the nature and occurrence of geothermal resources: steam, hot water, geopressure, hot dry rock, and magma[4-5].

Conventional methods of geothermal utilization typically include hydrothermal intermediate-depth geothermal systems (involving water extraction and heat utilization, cascade utilization, and heat extraction without water consumption), buried pipe intermediate-depth geothermal systems (involving heat extraction without water extraction, using coaxial or U-shaped buried pipes), and shallow geothermal heat pump systems[6,7]. Shallow geothermal systems primarily rely on the seasonal energy balance of soil to provide heating in winter and cooling in summer, making them suitable for projects requiring simultaneous heating and cooling. Intermediate-depth geothermal systems are primarily used for single-purpose heating projects. Current approaches in intermediate-depth geothermal heating commonly utilize two forms: 'heat extraction without water extraction' as depicted in Figure 1, and "heat extraction without water consumption" illustrated in Figure 2. The "heat extraction without water extraction" method can further be differentiated by pipe configuration, such as coaxial and U-shaped buried pipes. As the geothermal heating market evolves and with advancements in drilling and mining technologies, there is emerging interest in techniques like "multi-point interconnected heat extraction without water extraction" geothermal heating technology. However, compared to the aforementioned two heat exchange methods, this technology is still in the early stages of practical implementation.

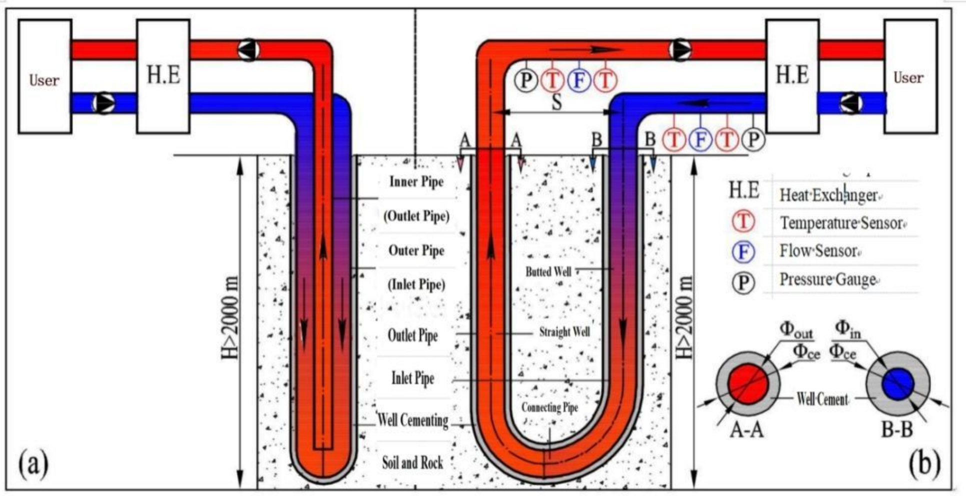

Figure 1. "Heat extraction without water extraction" utilization method

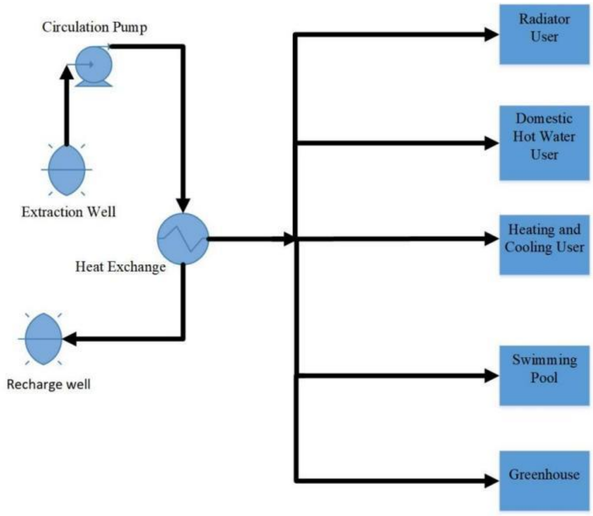

Figure 2. "Heat extraction without water consumption" utilization method

Figure 1 shows the "Heat without water" geothermal utilization, the current commonly used form of"Concentric casing heat" and "U-type casing form"[8] , such use of closed system, it has no interference to groundwater system and can be applied to the geology of geothermal reservoir without water, difficult to recharge or extremely difficult to recharge. Figure 2 shows a diagram of a "Heat without water" utilization technique that can meet a variety of end-use requirements. The technology of "Taking heat without consuming water" appears in pairs with the recharging wells. The domestic and foreign scholars have carried out extensive research on the productivity prediction and parameter optimization of the recirculating heat taking technology. Based on the single porosity theory, Cao et al. [9] established a 3D thermal-fluid-solid coupling model, and found that when the reservoir temperature exceeds 170 ° C, the thermal power is expected to reach 20 MW. Compared with the technology of "Taking heat without taking water", the technology of "Taking heat without taking water" is non-contact in the process of taking heat in closed cycle because of the heat exchange between fluid and high temperature rock of reservoir, compared with the method of " Taking heat without water", the capacity of the closed cycle is relatively limited. The results show that the heat extraction power of the open cycle system may be more than 10 times that of the closed cycle system [10,11]. Dezhou is rich in groundwater and geothermal resources. Considering the factors of heating capacity, construction investment and later operation cost, the Pingyuan County heating project adopts the technology of "Taking heat without consuming water".

Current Status of Geothermal Resources in Dezhou

China is rich in geothermal resources in the middle and deep strata, with an annual recoverable amount equivalent to 1.865 billion tons of standard coal[12], Geothermal resources are predominantly found in three main areas: the northwest depression geothermal zone, the eastern uplift geothermal zone, and the western uplift geothermal zone. In Shandong Province for a detailed overview of geothermal distribution.

As indicated in Figure 3, this project is situated in the northwest depression geothermal zone of western Shandong, specifically in Pingyuan County, Dezhou City. Dezhou City is renowned for its abundant geothermal reserves, totaling approximately 3,084 ×107 GJ, making it a significant focal point for geothermal resource enrichment in Shandong Province. Known for its extensive distribution, abundant reserves, and favorable exploitation conditions, geothermal resources were first discovered here in 1980, with formal exploration and development commencing in 1996. City-wide surveys confirm substantial resources, with a total geothermal resource volume reaching around 50 billion m^3, contributing 21% of the province's geothermal capacity. Geothermal wells in Dezhou City typically range in depth from 1300 to 1700 meters, yielding water temperatures between 50°C and 70°C. Under optimal recharging conditions, the city can sustain an annual exploitation capacity of about 500 million m^3. Dezhou City stands out as the most concentrated hub of geothermal resources in Shandong Province, leading the nation in terms of resource reserves, comprehensive development and utilization, deployment of recharging infrastructure, and technological advancements. Its scale of development and utilization ranks at the forefront nationwide.

Determination of Recharge Well Parameters

Geothermal resources are characterized by inherent uncertainties, with some areas within geothermal zones lacking sufficient resources. Current standards for intermediate-depth geothermal utilization projects are primarily guided by local regulations in Beijing and Shanxi Province. Considering the practical integration of projects with regulatory requirements, this project's design aligns with the local standards of Shanxi Province. According to the Technical Specifications for Intermediate-depth Geothermal Heating Engineering (DB14/T2386-2021), Section 4.1.1 specifies that "prior to scheme design for intermediate-depth geothermal heating projects, comprehensive data collection and site surveys are essential, including geological surveys of intermediate-depth geothermal energy resources." In April 2024, trial well drilling was conducted near the Beiyuan Energy Station, as illustrated in Figure 4. The drilling rig, depicted in Figure 3, incorporates not only the main structure but also complementary power generation and equipment facilities, covering an operational area of approximately 25x45 meters.

Figure 3. Drilling rig for water intake and recharge wells

The "heat extraction without water consumption" technique necessitates a "recharge-driven extraction" approach, ensuring that water intake is balanced by equivalent recharge at the same stratum level. Geothermal water wells are configured in paired formations, with the spatial layout of intake and recharge wells determined by Section 7.1.2.6 of the Technical Specification for Intermediate-depth Geothermal Heating Projects (DB14/T2386-2021), emphasizing the critical impact of well spacing on hydraulic head. Figure 4 illustrates how different well spacings affect hydraulic head, water temperature, investment, and other variables. The figure clearly shows that the temperature differential between water intake and recharge stabilizes within approximately a 400-meter well spacing. Therefore, this project adheres to a 400-meter interval for both water intake and recharge wells based on these findings.

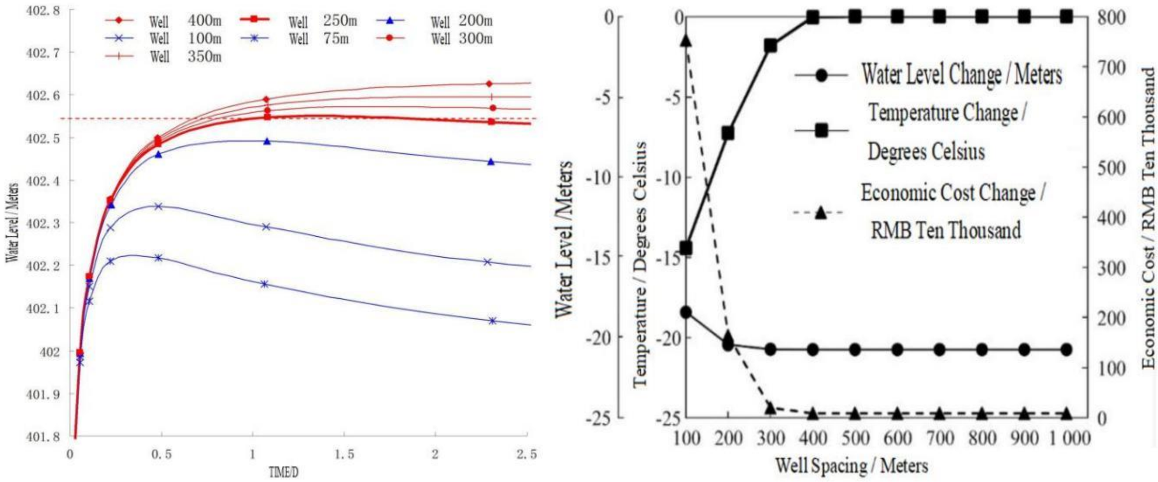

Figure 4. Chart of the influence of different well spacings on hydraulic head

The observational data from the test wells in this project have been completed. The depth of the water intake and recharge wells is 1700 meters, with a spacing of 400 meters between intake and recharge points. The water intake rate is 100 m3/h, and the water temperature at intake is 57°C. Based on these test well parameters, the project's design parameters are set at an intake rate of 80 m3/h and an intake water temperature of 56°C.

DETERMINATION OF ENERGY STATION SETUP

Confirmation of Current Energy Supply Status and Load Index

In the western urban area, the primary centralized heating source is the Yangmei Power Plant. The plant operates a total of 5 coal-fired boilers (3×75T/h + 2×220T/h) along with 2×12MW extraction-condensing units and 1×40MW back-pressure turbine-generator unit. In addition to fulfilling the heating demands of the western urban area, the plant supplies steam to approximately 18 enterprises in the chemical industrial park and surrounding areas, with steam outputs ranging from 8 to 16 tons per hour. However, due to prolonged periods of low-load operation and the boilers' extended service life, steam production costs are relatively high, resulting in increased energy consumption for the heating system and sustained financial losses. Each heating season requires a subsidy of over twenty million yuan from county finances, imposing significant fiscal strain.

Figure 5. Heating status in the western urban area

In the western urban area of Pingyuan County, there is a steam-water heat exchange energy station located precisely within the coverage depicted in Figure 5. This facility utilizes steam from the Yangmei Power Plant, which is processed through heat exchanger units to provide heating for the western urban area. With the closure of the Yangmei Power Plant, there is an urgent need to find high-quality alternative heat sources that align with national industrial and environmental policies for the existing centralized heating system in the western urban area.

In the western urban area, heating users primarily include residential complexes, schools, government offices, and commercial establishments, totaling a built-up area of 2.02 million square meters. For this renovation project, heating demand is directly determined from historical operational data without further computation. Based on past operational records, the comprehensive heating energy consumption index for Pingyuan County's western urban area is established at 43 W/m². Accordingly, the total load for the energy station in this project is calculated at 43 W/m².

Division of New Energy Station Areas

As part of this renovation project, careful consideration has been given to ensure the optimal reuse of existing municipal heating pipelines in determining the division and construction sites for the new energy stations. This strategic approach not only significantly reduces project costs but also minimizes the construction timeline. After reorganizing the existing network in the western urban area, it has been divided into two distinct zones: the Beiyuan Energy Station and the Nancheng Park Energy Station.

Based on the heating area indicators established in the previous section, calculations have been conducted to determine the heating load allocation for both the Beiyuan Energy Station and the Nancheng Park Energy Station. The total heating load for each station is shown in Table 1.

Table 1. Thermal load table of energy stations

Summary Table of Heating Heat Loads in the Western Urban Area					
Serial Number	Station	Designed Heating Area (10,000 m²)	Comprehensive Heating Heat Index (W/m²)	Designed Maximum Heat Load (KW)	Average Heat Load (KW)
1	Beiyuan Energy Station	102	43	43860	32456
2	Nancheng Park Energy Station	100	43	43000	31820
3	Total	202		86860	64276

According to Table 1, the total thermal demand for Beiyuan Energy Station and Nancheng Park Energy Station is 43.86 MW and 43 MW, respectively. With an average load factor of 0.74, the average heating requirements are 32.5 MW and 31.8 MW, respectively.

Determination of Geothermal Well Locations

Based on the test well data, the extraction water temperature is 56°C with a flow rate of 80 m3/h per well. The usable thermal power Wt per well can be calculated using the following formula:

$$Wt=1.163Q(T-Th1) + 1.163Q(Th1-Th2) (COP/COP-1) [13] \quad (1)$$

Where:

Wt: Thermal power (kW)

Q: Geothermal fluid extraction rate (m3/h)

T: Fluid temperature, set at 56°C

th1: Geothermal tailwater temperature at the first heat exchanger, set at 42°C

th2: Return water temperature, set at 16°C

COP: Coefficient of Performance of the heat pump

1.163: Unit conversion factor

The energy system configuration influences the heating coefficient of the water-source heat pump unit in this project. For the purposes of this chapter, COP is provisionally set at 4.7 W/W based on an intermediate water temperature of 15/7.

The calculation yields: Wt = 4279.84 kW, indicating that each geothermal well, paired with the heat pump unit, can provide thermal energy of 4279.84 kW. According to the heating load requirements shown in Table 1, each energy station will require approximately 24 wells to meet the heating demand. The ratio of extraction to return wells is set at 1:1. Refer to Figure 6 for the locations of the drilling sites.

Figure 6. Locations of extraction and recharge wells

DETERMINATION OF SYSTEM CONFIGURATION

Geothermal water heating projects aim to maximize thermal output by typically widening temperature differentials to ensure efficient utilization of geothermal water through recharge. In this project, water is extracted at 56°C with a temperature differential of 40°C between extraction and recharge, and a recharge water temperature of 16°C. The municipal supply return water temperature is set at 53/40°C, while the first-stage heat exchanger's supply return water temperature is 56/42°C. However, this study categorizes the system configuration into System 1 and System 2 based on differing intermediate water temperatures and contrasts and analyzes these two utilization approaches. System 1 operates with intermediate water temperatures of 15/7°C for stages one and two, while System 2 employs intermediate water temperatures of 40/26.8°C for stage two and 26.8/14°C for stage three [14,15].

System Scheme 1

The schematic diagram for Scheme 1 is illustrated in Figure 7. As shown, the system is divided into the Primary Network System, the Intermediate Water System, and the Secondary Network System.

Primary network system

Geothermal water at 56°C from deep wells undergoes desanding and filtration before entering the direct supply water-water plate heat exchanger for thermal exchange. After releasing heat, the temperature decreases to approximately 42°C. The tailwater then enters the intermediate water-water plate heat exchanger, where its temperature further reduces to around 16°C. It is then pressurized by a booster pump and treated by the geothermal tailwater treatment unit before being reinjected.

Intermediate water system

The intermediate water acts as a thermal conduit between the heat source and the circulating water in the thermal network. It absorbs heat from the geothermal well tailwater through the intermediate water-water plate heat exchanger. The heated intermediate water is then directed to the evaporator of the high-temperature heat pump unit for heat dissipation. After releasing heat, the pressurized intermediate water returns to the intermediate water-water plate heat exchanger for continuous circulation. The geothermal water, having undergone primary heat exchange to reach 42°C, passes through the heat exchanger and is cooled to 16°C before being reinjected. Starting at 7°C, the intermediate water enters the heat exchange unit and warms up to 15°C after exchanging heat with the geothermal water, before entering the heat pump unit.

Secondary network system

After purification by a dirt remover, the return water from the secondary network is pressurized by a circulating water pump. One portion enters the direct supply water-water plate heat exchanger for heating, while another portion enters the condenser of the high-temperature heat pump unit. The heated water is then distributed through the secondary network to various heating users.

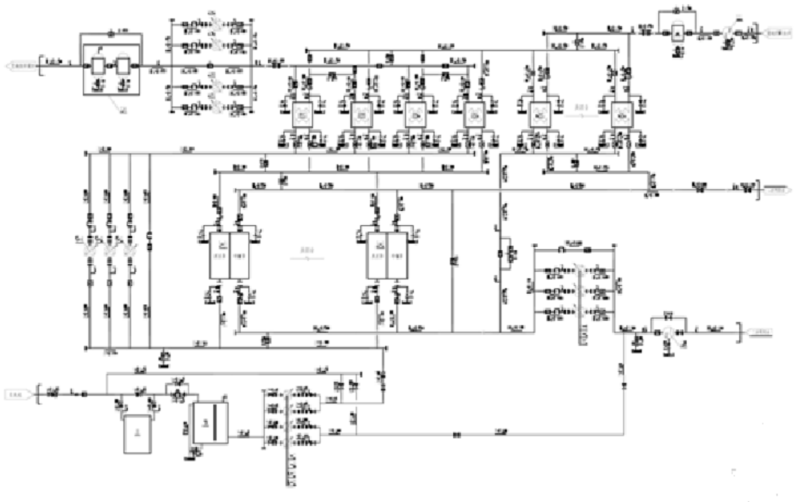

Figure 7. System scheme 1 schematic diagram

According to Formula 1 calculations, System Scheme 1 has a well-heating capacity of 4279.84 kW. This type of system, due to its lower intermediate water temperature and relatively lower unit efficiency, has a reduced capacity for well-heating. However, the technical planning parameters for the water-source heat pump units remain consistent, and the smaller heat exchange area for the intermediate water plates saves station area.

System Scheme 2

The schematic diagram for Scheme 2 is shown in Figure 8. As illustrated, the system is primarily divided into the Primary Network System, the Secondary Heat Pump System, the Tertiary Heat Pump System, and the Secondary Network System.

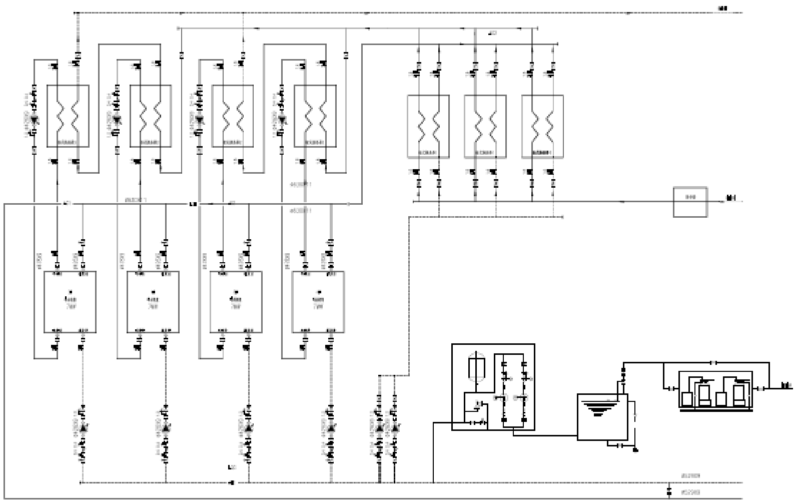

Figure 8. System scheme 2 schematic diagram

Primary network system

Geothermal water at 56°C from the deep well undergoes sand removal and filtration before entering the direct supply water-to-water plate heat exchanger. After heat exchange, the water temperature drops to approximately 42°C. This tailwater then enters the intermediate water-to-water plate heat exchanger for further heat exchange, reducing the temperature to around 16°C. The tail water is then pressurized by a pump and processed by the geothermal tail water treatment unit before reinjection.

Secondary heat pump system

This system comprises the secondary intermediate water system and the heat pump unit. The primary side supply water for the secondary heat exchanger is provided by a submersible pump from the geothermal extraction well, with inlet and outlet temperatures of 42/29°C. The secondary intermediate water temperature is maintained at 40/26.8°C. The secondary intermediate water enters the heat pump unit for temperature boosting and operates in parallel with the primary heat exchange system.

Tertiary heat pump system

This system comprises a tertiary heat exchanger and a heat pump unit. The primary side supply water for the tertiary heat exchanger is provided by a submersible pump from the geothermal extraction well, with inlet and outlet temperatures of 29/16°C. The tertiary intermediate water temperature is maintained at 26.8/14°C. The tertiary intermediate water enters the heat pump unit for temperature boosting and operates in parallel with the primary heat exchange system and the secondary heat pump system.

Secondary network system

After passing through a dirt separator for filtration, the return water in the secondary network is pressurized by a circulation pump. A portion of this water is heated through the direct supply water-to-water plate heat exchanger, while the remainder is heated by the condenser of the high-temperature heat pump unit. The heated water is then distributed throughout the secondary network to heating users.

According to Formula 1, the heat supply capacity of System Scheme Two is 5,645.75 kW. This is primarily due to the increased intermediate water temperature, which enhances the coefficient of performance (COP) of the heat pump units, thereby improving the overall heat supply capacity. While Scheme Two significantly outperforms Scheme One in terms of heat supply capacity, it requires a larger heat exchanger area, occupies more space, and involves different types of secondary and tertiary heat pump units.

Comparative Analysis

Both Scheme 1 and Scheme 2 have their respective advantages and disadvantages. With ample land area available for the project's energy station and without concern for the space occupied by heat exchangers, we have analyzed the initial investment and operational costs of both plans. Scheme 2 reduces investment costs by RMB 3.6 million compared to Scheme 1 and decreases operational costs by RMB 2.4/m². Therefore, considering both initial investment and operational costs, Scheme 2 offers significant advantages. Consequently, Scheme 2 has been selected as the preferred system plan for this project.

BENEFIT ANALYSIS

Energy Savings

Since the 12th Five-Year Plan, national policies have consistently emphasized dual control of energy consumption to reduce both energy intensity and overall consumption levels. Table 2 illustrates the energy-saving potential of this project, indicating a savings of 3.08 tons of standard coal equivalent (tce/a) compared to coal-fired boilers.

Table2. Energy consumption analysis for clean heat source replacement in Xicheng district of Pingyuan county

Category	Heating Source Type	Heating Building Area (10,000 m²)	Maximum Heat Load (GJ/h)	Average Heat Load (GJ/h)	Comprehensive Heat Efficiency	Standard Coal Consumption (tce/a)
Traditional Coal-Fired Heating	Coal-Fired Boiler	202	309.6	229.1	0.7	34,900
Geothermal Deep Well Water Heating	Deep Geothermal Cascade Utilization	202	309.6	229.1	6	4,100

Emission Reduction

This project aims to enhance renewable energy utilization through the use of intermediate-depth geothermal resources for centralized heating, achieving a 100% renewable energy utilization rate. The emission reduction impact is detailed in Table 3. Switching to intermediate-depth geothermal heating can effectively reduce annual carbon emissions by 91,000 tons.

Table 3. Analysis of emission reduction from clean heat source replacement in Xicheng district of Pingyuan county

Serial No.	Pollutant Type	Emission Reduction (t/a)
1	CO2	91,000
2	SO2	837.6
3	NOX	244.3

DISCUSSION

In the era of dual carbon goals, the adoption of renewable energy for heating is increasingly mandated, aligning with both the national 14th Five-Year Energy Plans and local policies that endorse intermediate-depth geothermal heating solutions specifically. However, the formulation of plans for intermediate-depth geothermal heating projects requires a cautious approach. System designs should meticulously incorporate considerations of geological conditions, regulatory requirements, and the need to depart from conventional fossil fuel-based heating ideologies.

(1) From a cost-efficiency standpoint, the feasibility of "heat extraction without water consumption" surpasses that of methods of “heat extraction without water extraction”. The heating capacity of wells in Pingyuan County is 5645.75 kw, which can meet the heating demand of 130,000 m2.

(2) When employing "heat extraction without water consumption" technology, energy station systems should prioritize the cascaded utilization of geothermal water. Maximizing the intermediate water temperature enhances the efficiency of heat pump units, thereby optimizing the capability to extract heat from wells. The first scheme is 4279.84 kw, the second scheme is 5645.75 kw. The second scheme is recommended as the optimal form of medium-deep geothermal heating system.

(3) Prior to finalizing designs for intermediate-depth geothermal heating projects, it is crucial to collect and conduct comprehensive data collection and site assessments on project sites and surrounding conditions. This includes conducting detailed geological surveys to assess intermediate-depth geothermal energy resources thoroughly, in the heating project of Ping yuan County, the distance between water intake and recharge wells is determined to be no less than 400m by well drilling exploration.

(4) Compared to natural gas boiler heating projects, intermediate-depth geothermal initiatives often require higher upfront investments. Therefore, conducting thorough research into local policies is crucial to effectively leverage available support and ensure the project's viability.

REFRENCES

[1] Zhang Q. Chen S Y. Tan Z Z, et al. Investment strategy of hydrothermal geothermal heating in China under poli-cy, technology and geology uncertainties. Journal of Cleaner Production, 2019, 207: 17-29.

[2] Ragnarsson Á, Steingrímsson B, Thorhallsson S. Geothermal development in Iceland 2015-2019/Proceedings World Geothermal Congress. Hague: International Geothernal Association, 2020: 1-15.

[3] Moeck I, Bracke R, Weber J. The energy transition from fossil fuels to geothermal energy-A german case study. [2022-1001]. https://www.geotis. de/ homepage/ sitecontent/ info/ publication_data/ congress/ congress_data/ Moeck_ WCC_ 2020_Energy_Transition. pdf.

[4] Song X Z, Wang G S, Shi Y, et al. Numerical analysis of heat extraction performance of a deep coaxial borehole heat exchanger geothermal system. Energy, 2018,164: 1298-1310.

[5] Thomasson T, Abdurafikov R. Dynamic simulation and techno-economic optimization of deep coaxial borehole heat exchangers in a building energy system. Energy and Buildings, 2022, 275:112457

[6] Zhao Z H, Dou Z H, Liu G H, et al. Equivalent flow channel model for doublets in heterogeneous porous geothermal reservoirs. Renewable Energy, 2021, 172: 100-111.

[7] Liu Y G, Long X L, Liu F. Tracer test and design optimization of doublet system of carbonate geothermal reservoirs. Geothermics, 2022, 105:102533.

[8] Thomasson T, Abdurafikov R. Dynamic simulation and techno-economic optimization of deep coaxial borehole heat exchangers in a building energy system. Energy and Buildings, 2022, 275: 112457

[9] Cao W J, Huang W B, Jiang F M. A novel thermal- hydraulic-mechanical model for the enhanced geothermal system heat extraction. International Journal of Heat and Mass Transfer,2016,100:661-71.

[10] Wang G S, Song X Z, Song G F, et al. Analyzes of thermal characteristics of a hydrothermal coaxial closedloop geothermal system in a horizontal well. International Journal of Heat and Mass Transfer, 2021, 180:121755.

[11] Wang Y R, Wang Y M, You S J, et al. Operation optimization of the coaxial deep borehole heat exchanger coupled with ground source heat pump for building heating. Applied Thermal Engineering, 2022, 213: 118656.

[12] Guiling Wang, Wei Zhang, Jiyu Liang n, etc. Assessment of geothermal resource potential in China. Journal of the Earth,2017,38(4):449-450,134,451

[13] YUAN Andong, TANG Wenlong, WANG Lijuan, WANG Haitao Study on Performance Simulation of Heat Exchanger in Middle and Deep Geothermal Well Journal of Anhui Jianzhu University 2022,2095-8382

[14] Zhang Hongyu; Gan Fei; Huang Guangqin, et al. Study on Heat Storage Performance of Phase Change Reservoir in Underground Protection Engineering, Energies. 2022. Volume 15, Issue 15. PP 5731-5731.

[15] Dmitry E. An engineering model of heat transfer through a turbulent falling liquid film for a condensing vapor flow. Chemical Engineering Research and Design, 2022,1871-8.