Postprint: Research on Geothermal Resources and Their Development and Utilization in Xiong' an New Area

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Date: 2017-11-17T00:00:00+00:00

Abstract

Xiong' an New Area is endowed with abundant geothermal resources that are relatively accessible for exploitation, thereby holding significant potential for contributing to ecological civilization development. The shallow (<200 m) geothermal resources in the region are suitable for development; within the deep (200–3,000 m) geothermal systems, both sandstone and carbonate reservoirs exhibit substantial thermal capacities and are amenable to exploitation; ultra-deep (>3,000 m) geothermal resources also demonstrate exploitation potential. In Xiong County of Xiong' an New Area, a single project leveraging large-scale karst thermal reservoirs for district heating has achieved the world's largest heating capacity (4.5 million m^2). This paper contends that Xiong' an New Area should enhance geothermal resource exploration efforts, prioritizing ultra-deep carbonate thermal reservoirs; regarding utilization, measures should be adapted to local conditions with rational allocation of deep and shallow resources, while emphasizing environmental protection and coordinating relationships with other resource utilization patterns; concurrently, geothermal energy storage technologies should be developed to establish a new clean energy utilization paradigm centered on geothermal energy with multi-energy complementarity, namely a "geothermal+" framework.

Full Text

Special Issue: Science & Technology Supporting Xiongan New Area' s Planning and Construction

Geothermal Resources and Development in Xiongan New Area

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Abstract
Xiongan New Area is rich in geothermal resources, which may play a key role in the construction of ecological civilization. The shallow geothermal energy (<200 m), deep geothermal energy stored in sandstone and karstic reservoirs are rich and suitable for exploitation and utilization. The deep carbonate geothermal resources are particularly large and easy to exploit. Geothermal resources stored in super-deep layers (>3000 m) also show good potential. Xiongxian County, located in Xiongan New Area, has pioneered large-scale district heating using karstic geothermal resources, representing the world' s largest single project with a total geothermal heating capacity of 4.5×10^{6} m^2. The authors believe that future geothermal exploration should be enhanced, especially for super-deep carbonate reservoirs. In utilizing geothermal energy, measures should be adapted to local conditions with rational allocation of shallow and deep resources. Environmental protection must be prioritized, and relationships with other energy resources should be coordinated. Simultaneously, geothermal energy storage technologies should be developed to gradually construct a new clean energy utilization pattern with geothermal energy as the main component and multiple complementary energy sources forming a "Geothermal+" system.

Keywords
Xiongan New Area, large-scale karstic geothermal reservoirs, geothermal district heating, large-scale geothermal exploitation, reinjection technology, geothermal tracing, monitoring of geothermal reservoirs

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Introduction

The establishment of Hebei Xiongan New Area represents a major decision by the Party Central Committee with Comrade Xi Jinping at its core, based on national development needs in the new era—a millennium-long plan and a matter of national importance. To build an eco-friendly city where blue and green merge seamlessly, comprehensive air pollution prevention and other environmental protection measures must be implemented.

Winter is the season when smog frequently occurs in North China. On December 21, 2016, at the 14th meeting of the Central Financial and Economic Affairs Leading Group, General Secretary Xi Jinping stated: "Promoting clean heating in northern China during winter concerns the warmth of the masses, whether smog days can be reduced, and represents an important component of the energy production and consumption revolution as well as rural lifestyle transformation." He clearly identified clean heating as a critical link in smog control at the source.

Based on long-term research, our team clarified as early as the 1980s that North China is rich in geothermal resources, with the Beijing-Tianjin-Hebei region being the most abundant. Since the 21st century, taking Xiongxian County in Xiongan New Area as an example, we have conducted concentrated research on evaluation and development key technologies for large karstic reservoirs. Both theoretical models and field practice demonstrate that large karstic reservoirs developed in the widely distributed carbonate rock formations in North China feature enormous scale and excellent resource quality, enabling balanced production-reinjection exploitation at scale—a rare global phenomenon that can support geothermal heating as an industry to replace coal and alleviate regional smog. This paper briefly reviews and analyzes North China geothermal research since the 21st century, particularly regarding large karstic reservoirs, and summarizes key reservoir engineering technologies from geothermal development in the Xiongxian area, offering recommendations for future work.

Geothermal Resources and Reserve Estimation in Xiongan New Area

Compared with fossil fuels, geothermal energy offers significant socioeconomic and environmental advantages, producing virtually no pollutants or large amounts of CO_2 during utilization. Unlike solar and wind energy, geothermal energy is continuous and stable, available 24 hours a day, 365 days a year, with high utilization efficiency enabling "cogeneration" to simultaneously supply heating and hot water [1].

The Chinese Academy of Sciences geothermal team has conducted long-term research in North China. During the 6th Five-Year Plan period (1980–1985), systematic ground temperature measurements and terrestrial heat flow tests were performed, petroleum exploration geothermal data were compiled, relatively high-temperature zones were delineated, geothermal field mathematical modeling was conducted, and the region' s tectonic-thermal evolution characteristics were investigated [2–4]. In the 1990s, research on geothermal resources in the Jidong Oilfield was carried out (enterprise-commissioned project). During the 11th Five-Year Plan (2005–2010), research on heat hazard prevention in deep coal mines in North China was conducted (National "973" Program), focusing on coal-carbonate reservoir composite structures to study heat accumulation mechanisms and distribution characteristics. During the 12th Five-Year Plan (2010-2015), research on geothermal issues in CO_2 geological sequestration in the Bohai Bay Basin was performed (National "863" Program), along with studies on typical reservoir genesis analysis and development technology (enterprise-commissioned project), and research on large karstic reservoir response to large-scale exploitation (National Natural Science Foundation of China). Additional fundamental research included "Geothermal Model Constraints on North China Craton Destruction" (NSFC-funded).

Based on this extensive research, our team discovered that Xiongan New Area possesses extremely rich geothermal resources. Within the economic depth of 3,000 m, three types of geothermal resources and reservoirs are available for utilization:

1. **Shallow geothermal energy** (<200 m): Can be combined with ground-source heat pump technology for energy efficiency. Ground-source heat pump heating efficiency is typically four times higher than conventional air conditioning and twice that of air-source heat pumps. This utilization method employs buried pipe heat exchange, causing no environmental damage while achieving significant electricity and coal savings. Shallow geothermal energy in Xiongan is suitable for utilization based on rational underground space allocation.

2. **Sandstone reservoirs** (200–3,000 m): Can be exploited through pumping and reinjection for heating, replacing coal and reducing smog. However, these reservoirs have limitations—reinjection is difficult in some areas, with an average reinjection rate of only 30%, meaning only about 30 m^3 of every 100 m^3 of extracted hot water can be successfully reinjected. The remaining portion, if discharged to surface water bodies, causes pollution and fails to meet clean energy requirements. Therefore, such resources should be used cautiously, with production policies based on reinjection capacity.

3. **Carbonate reservoirs** (1,000–3,000 m): The Mesoproterozoic and Neoproterozoic karst (karstic) systems are particularly well-developed, forming large karstic reservoirs suitable for heating. In Xiongan, the widely distributed Wumishan Formation dolomite reservoirs reach total thicknesses of thousands of meters, with temperatures exceeding 60°C at 1,000 m depth. Their greatest advantage is high water yield, with 100% reinjection potential, enabling cyclic utilization.

Resource estimates for these three geothermal types in Xiongan are shown in Table 1 . Shallow geothermal resource quantities reference China Geological Survey evaluation results [5], while sandstone and carbonate reservoir resources are estimated by analogy from the Xiongxian geothermal field [6–8].

Genesis and Evaluation of Large Karstic Geothermal Reservoirs

Based on extensive hydrogeological, geophysical, and geochemical work, we established a "binary heat accumulation" genetic model for Xiongan' s geothermal resources, represented by the Niutuozhen geothermal field (Figure 1 [Figure 1: see original paper]). One component is rock thermal conductivity, the other is basin-scale groundwater circulation. The abundant geothermal resources in the Bohai Bay Basin formed through geothermal redistribution under this dual-mechanism coupling. The heat source for Xiongan' s geothermal resources is the high heat flow background of rift basins, with heat transfer dominated by conduction in Cenozoic cap rocks and convection in bedrock reservoirs—thus constituting a "convection-conduction geothermal system" [7,9]. The large karstic reservoir is primarily Jixian System, overlain by Quaternary and Neogene cap rocks with a relatively independent groundwater circulation system. This understanding of geothermal resource formation conditions provides a scientific basis for Xiongan' s geothermal development planning and offers prospective information for super-deep geothermal exploration.

Recent geochemical and isotopic studies of Xiongan' s geothermal fluids provide important information on material sources and formation conditions, plus opportunities to estimate super-deep reservoir temperatures. We believe geothermal gases are mainly crust-derived, with relatively high helium volume content (0.08%-0.52%), of which 5%-8% originates from the mantle. Wumishan Formation carbonate reservoir geothermal water is Cl-Na type, with gas mainly composed of CH_4, N_2, and CO_2, where CO_2 originates from carbonate thermal metamorphism. The addition of thermogenic CO_2 promotes karst development in deep carbonate reservoirs. Based on helium isotope composition, mantle-derived heat flow accounts for 48%-51% of surface heat flow in the region' s crust-mantle thermal structure. Chemical geothermometer calculations indicate current production layer temperatures of 66-108°C [10-13]. Based on CO_2/N_2 gas component geothermometry and carbon isotope geothermometry between CO_2-CH_4, deep reservoir temperatures average 163°C and 153°C, respectively , providing new information for super-deep layer exploration.

Advanced Geothermal Exploitation Key Technologies and Demonstration Projects

Geothermal resource development technology has evolved through two generations. The first generation featured direct extraction, direct supply, and direct discharge, but has been abandoned due to low environmental standards. The second generation combines extraction with reinjection, using heat without consuming water, meeting high environmental standards and gaining government promotion. In China, shallow geothermal utilization technology is mature—most locations can implement it with proper quality control. Practice generally encourages ground-coupled heat pump systems using buried pipes while restricting groundwater-source heat pump systems requiring water extraction to protect valuable groundwater resources. For medium-deep sandstone reservoirs, second-generation technology is commonly used where reinjection conditions are favorable, with continuous reinjection technology improvements. For karstic reservoirs in bedrock, a scaled, industrialized geothermal development technology system has been formed and applied.

Since 2009, Sinopec Green Energy Geothermal Development Co., Ltd. has invested in the Xiongxian geothermal heating project, with our CAS geothermal team providing continuous technical support and services. After several years of effort, China' s first "smokeless city" using geothermal heating to replace coal was established. The Xiongxian demonstration project, based on a government-industry-academia-research-application partnership, first achieved both high-efficiency geothermal utilization and near-zero emission clean energy goals, operating smoothly for eight years. By early 2014, the National Energy Administration began promoting the Xiongxian model to northern regions. In 2016, Xiongxian County had a population of 90,000, with 68 geothermal wells (24 reinjection wells), forming a heating capacity of 4.5 million m^2, basically achieving full geothermal heating coverage. Xiongxian employs second-generation technology with nearly 100% reinjection, using heat without consuming water. Project highlights include: complete urban geothermal heating coverage, world' s largest project scale (4.5 million m^2 heating capacity, currently operating at 2.8 million m^2, serving 90,000 people), average single-well heating capacity of 100,000–150,000 m^2, and 100% tailwater reinjection to the same layer.

Over the past 20 years, China' s total direct geothermal utilization has consistently ranked first globally, currently more than double that of the United States. Moreover, main heating system equipment is domestically produced, providing a solid technical foundation. Through continuous exploration, a series of reservoir reinjection technologies supporting large-scale development has been formed. Xiongxian geothermal field reinjection began in 2010, with cumulative reinjection reaching 23.83 million m^3 by the end of 2016. Tailwater reinjection avoids surface discharge pollution and effectively slows reservoir pressure decline [14] (Figure 2 [Figure 2: see original paper]).

Xiongan' s karstic reservoirs exhibit strong heterogeneity, making connectivity between production and reinjection wells difficult to determine. Tracer technology can quantify migration parameters, effectively characterize reservoir fluid features, investigate hydraulic connections between reinjection and production wells, and predict potential cooling of production wells from long-term reinjection. Since 2011, our team conducted three multi-well tracer tests in the Xiongxian geothermal field, obtaining effective parameters for connectivity within the karstic reservoir, including channel length, flow velocity, and longitudinal dispersivity, providing a scientific basis for numerical simulation studies of well spacing and layout [15,16]. Test results revealed permeation velocities in different directions from reinjection wells (Figure 3 [Figure 3: see original paper]) and directions with good connectivity between production and reinjection wells (Figure 4 [Figure 4: see original paper]).

Rational well layout and optimal well spacing are critical for optimized geothermal field exploitation, affecting production costs and field lifespan. We established a methodology to evaluate optimal layout and spacing: based on a geothermal geological model, numerical simulation technology is used to model temperature and pressure responses to different production-reinjection scenarios (Figures 5 [Figure 5: see original paper] and 6 [Figure 6: see original paper]), then using an economic model with the objective function of minimizing losses from production temperature decline and water level drop caused by reinjection, optimal well spacing and exploitation patterns are determined [17]. This method indicates that for the Xiongxian geothermal field, the optimal production-reinjection well distance in doublet mode is 400 m (Figure 7 [Figure 7: see original paper]).

Recommendations for Geothermal Development in Xiongan

Xiongan possesses abundant geothermal resources, particularly extensive, large-capacity, high-quality, high-temperature karstic reservoirs that are easy to exploit and reinject. The area has already taken the lead in geothermal utilization with successful experience that, through national promotion, will guide energy structure transformation. Specific recommendations include:

Strengthen Leadership and Policy Support
Implement necessary policy measures and financial support to guide local governments in expanding promotion, issuing preferential policies, encouraging enterprise participation, improving development efficiency, and gradually forming a green geothermal energy industry. To achieve faster technological progress and broader application, we recommend incorporating geothermal resource utilization into overall air pollution prevention planning.

Accurate Assessment and Resource Inventory
Although Earth' s total geothermal energy is enormous, its distribution is highly uneven. Economic and rational utilization requires identifying accumulation zones where geothermal energy can be effectively developed. Clear genetic model research and accurate reserve evaluation to continuously open new resource reserves form the foundation for large-scale sustainable geothermal utilization. Therefore, we recommend strengthening geothermal resource exploration to identify deeper reservoir development conditions and utilization potential.

Adapt to Local Conditions with Combined Shallow-Deep Resources
Geothermal utilization should consider resource conditions and heating demands, comprehensively evaluating the suitability of medium-deep and shallow geothermal energy. Principles include: (1) Xiongan should establish high-startpoint, high-standard, high-level geothermal development based on the Xiongxian model; (2) Low plot ratio residential areas can use shallow geothermal heating—ground-source heat pumps are new energy-saving technologies that should be fully utilized with rational underground space coordination; (3) Centralized office areas should adopt medium-deep geothermal heating.

Geothermal-Based Multi-Energy Complementarity
Strengthen long-term dynamic monitoring and quantitative reservoir simulation of geothermal systems. For sandstone and karstic reservoirs with less favorable development conditions, conduct research and testing on reservoir stimulation technologies. Simultaneously, encourage exploration of "Geothermal+" third-generation technology integrating geothermal energy as the main body with multiple clean energy sources.

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Note: Figure translations are in progress. See original paper for figures.