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A Centennial Review of Geothermal Resources Exploration and Development in China

WU Aimin, WANG Guiling, WANG Huang, WEN Dongguang, TIAN Tingshan, LI Shengtao, ZHANG Wei, YANG Li, ZHAO Jiayi

China Geological Survey, Beijing 100037, CHINA

waimin@mail.cgs.gov.cn

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ABSTRACT

China has a history of thousands of years for the utilization of hot springs. 2000 years ago, *Classic of Mountains and Seas* described the characteristics of hot springs. In the last hundred years, the exploration and development of geothermal resources in China have experienced three stages. Geothermal exploration plays an essential role in China's geothermal energy exploitation and industry development.

Hot springs investigation promoted direct utilization: The first document on hot springs by TIAN Beihu (1908) recorded 140 hot springs. 500 and 972 hot springs were recorded by ZHANG Hongzhao in 1926 and 1956, respectively. The Ministry of Geology established the first research team for geothermal resources in 1956 and compiled a map of China's Geothermal Water in 1959. The first geothermal exploration report was completed by No. 904 Geological Team of the Ministry of Geology in 1958. From then to the 1980s, a series of geological surveys of hot springs were carried out, and 3398 hot springs were documented in 1986. These exploration findings provided the technical foundation for directly utilizing geothermal resources.

Geothermal water exploration supported diverse utilization: In 1970, the Ministry of Geology promoted the exploration and development of geothermal resources in China, particularly the geothermal exploration in Tianjin and the geothermal power station in Fengshun, Guangdong. Since then, provincial geothermal water surveys and typical geothermal field explorations, such as Beijing, Tianjin, and Hebei, were carried out gradually. The first nationwide geothermal resource assessment was conducted by CHEN Moxiang and WANG Jiyang (1994). These research findings significantly promoted the diverse utilization of geothermal resources in China. The first high-temperature geothermal field was gradually explored at Yangbajain, Tibet, and then the first high-temperature geothermal power station was built successfully in 1977. The building area heated by geothermal water has reached 40 million m^2 in Tianjin.

Integrated geothermal energy exploration accelerated efficient development: Since 2000, comprehensive geothermal energy exploration has been implemented by China Geological Survey (CGS) to support the Sustainable Development Strategy and Beijing Green Olympics. The investigations showed that the total shallow geothermal resource in 336 major cities, the total geothermal water resource in 31 provinces, and the total potential of hot dry rock(HDR) resource up to depths of 3~10 km mainland China, were equivalent to 700 million, 1.86 billion, and 856 trillion tons of standard coal, respectively. The world's most extensive integrated energy system of ground source heat pump was built in Beijing's Sub-Center, and the total heating and refrigeration area reached 2.4 million m^2. A high-temperature HDR well with more than 200℃ was drilled in the Gonghe basin, Qinghai Province. It has realized technological innovation from exploration to experimental power generation. Several high-temperature geothermal fields also have been explored in Xiong'An, Tianzhen, Huizhou, etc.

CGS will speed up to promote geothermal resources exploration and utilization to support national energy security and Carbon Emission Peak and Carbon Neutrality.

1. INTRODUCTION

China is one of the earliest countries in the world to develop and utilize geothermal resources. The development and utilization of geothermal hot springs can be traced back to King You of Zhou (781-771 B.C.), the last ruler of the Western Zhou Dynasty. During the Warring States period, *The Classic of Mountains and Seas* recorded that "warm water began in Kongtong Mountains, which sat in the south of the town of Linfen, flowed into the Yellow River, from the north of Huayang. " In the Ming Dynasty, *The Travels of Xu Xiake*, a geographical masterpiece, gave a more detailed documentation of the geothermal hot springs outflowing from Jiuqitai in Eryuan, Yunnan. The scientific investigation and research on geothermal resources in China started late. Still, they developed rapidly, with a range of findings from hot spring investigation, and geothermal water exploration to HDR exploration and experimental power generation, effectively promoting the development and utilization of geothermal resources.

In the context of pursuing green and low-carbon development, and achieving the carbon emission peak and carbon neutrality goal, geothermal energy, as a future alternative energy source, has attracted widespread attention from the international community. In 2006, the Massachusetts Institute of Technology (MIT) released the report: *The Future of Geothermal Energy* and *Impact of Enhanced Geothermal Systems [EGS] on the United States in the 21st century*, which claimed that EGS featured by HDR could provide more than 100 million kilowatts of geothermal power generation capacity for the U.S. mainland. This publication became a "stimulant" to a new global geothermal exploration and development round. According to the research (Wang, 2023), concerning the PV subsidy power generation policy, it was predicted that by 2026, the share of geothermal energy in China's primary energy consumption structure would reach 3.6% to 5.6%, and the total geothermal heating and cooling area would reach 10 to 14 billion m^2. Furthermore, the geothermal industry would reduce the annual carbon emissions by about 500 million tons, equivalent to 5% of the total carbon emissions in China in 2020.

Based on the investigation and evaluation of the geothermal resources by the CGS, and relevant geological survey findings and historical documents, this paper reviews the 100-year history of geothermal resource survey in China, clarifies the characteristics of geothermal resources, and proposes the survey direction in the future.

2. REVIEW OF GEOTHERMAL RESOURCES INVESTIGATION

According to the investigation objects, the geothermal resource investigation in China in the last one hundred years can be roughly divided into three stages as described below.

2.1 The stage of hot spring investigation

Before the founding of the People's Republic of China, sporadic geothermal hot spring investigations were carried out. In 1919, Su Shen wrote "China's Volcanic Veins" with a list of hot springs in various provinces, recording 74 thermal springs formed by volcanoes. In 1926, Zhang Hongzhao of the Central Geological Survey published a paper entitled *The Distribution of Hot Springs in China and the Relationship with Geological Formation* at the Third Pan-Pacific Academic Conference, where 500 hot springs were registered. They were divided into three categories according to their temperature: higher temperature (characterized by constant boiling), lower temperature (characterized by warmth and suitability), and unknown temperature. Zhang counted the quantity of hot springs in every province and examined the geographical distribution, taking into account the impact of geological formations on the mainland. As a result, China's main hot spring distribution areas were classified into seven region: Fujian and Guangdong, Shandong and Liaodong Peninsula, Taihang Mountains, Yunmeng, Shanxi and Gansu, Yunnan and Guizhou, and Huaiyang. He discovered a pattern that indicated a higher occurrence of hot springs in areas where earthquake sources were present, and highlighted that the distribution and genesis for the existence of hot springs in China were impacted by geological structures, subterranean magmatic activities, and the interactions between the Earth's crust and mantle. (Zhang Hongzhao, 1935). After this, Zhang compiled the *Collection of Hot Springs in China* and published it in 1956, during which the number of recorded hot springs increased to 972 and survey data of Xinjiang, Tibet, and Changdu, and findings such as the geological conditions, temperature, water inflow, physical and chemical properties near the hot springs, were added.

After the founding of the People's Republic of China in October 1949, hot spring investigations and geothermal geology research started partly. In 1956, the Ministry of Geology took the lead in establishing the first geothermal mineral water research team in the Institute of Hydrogeology and Engineering Geology, and completed the first national mineral spring distribution map in 1959. From 1958 to 1959, No. 901 Geological Team and No. 904 Geological Team of the Ministry of Geology completed the *Report on the Hydrogeological Survey of Mineral Springs in Xiaotangshan, Changping County, Beijing* and the *Report on the Exploration of Hot Springs in Jimo, Shandong Province*, which became the first hot spring reports in China. In 1960 and 1972, the Institute of Geomechanics of the Ministry of Geology and the Institute of Geology of the Chinese Academy of Sciences, set up geothermal research groups to carry out basic geological research on geothermal heat, develop rock thermophysical property testing instruments and drilling and temperature measurement devices, and conduct research on geothermal gradients and geothermal heat flow tests, distribution characteristics of geothermal systems and formation mechanisms. In 1965, the Institute of Hydrogeology and Engineering Geology of the Ministry of Geology and Mines organized several units to compile the first national hot spring distribution map, analyzed and discussed the distribution characteristics and formation mechanism of hot springs in some areas, which took into account the distribution characteristics of hot springs in China. Since then until the 1980s, various geological departments and scientific research institutions in China have conducted geological surveys on hot springs. By 1986, a total of 3,398 hot springs were documented. In 1992, the Institute of Geology of the Chinese Academy of Sciences compiled a map of hot springs nationwide, based on data collection and field investigation, which provided the basis for subsequent geothermal investigation and research.

2.2 The stage focusing on geothermal water exploration

Moving into the 1970s, along with the global oil crisis, the first significant wave of geothermal resource investigation in China was initiated by Li Siguang, a well-known geologist and Minister of Geology. He started the Tianjin Geothermal Investigation Campaign, discovered geothermal anomalies in Wanglan Zhuang and Wanjia Matou, and completed geothermal field surveys. With the assistance and support of the UN Energy Development Agency, he conducted the geothermal field survey in Yangbajing, Tibet, and achieved a breakthrough in the high-temperature geothermal field survey. More than 20 provinces in China have completed geothermal resource screening and geological mapping, forming many geothermal geological survey data and results. From 1973 to 1976, the general scientific expedition to the Qinghai-Tibet Plateau of the Chinese Academy of Sciences carried out a thorough and detailed investigation of the surface thermal displays of geothermal activity on the Qinghai-Tibet Plateau, starting with the research on rare hydro-thermal explosions and geysers, and made a systematic analysis of the geochemical characteristics of springs in more than 200 hydro-thermally active areas. They analyzed the mechanism of intense hydro-thermal activity in Tibet from the perspective of plate tectonics, proposed the concept of the Himalayan Geothermal Belt for the first time, and illustrated the role of geothermal activity in theoretical studies of continental dynamics and in solving real problems (Tong Wei et al., 1981; Yao Zujin et al., 1986; Zhao Wenjin et al., 2002; Duo Ji, 2003; Liu Zhao, 2014; Long Denghong et al., 2021; Yu Piaoluo et al., 2021; Hu Zhihua et al., 2022). In 1979, the Institute of Geology of the Chinese Academy of Sciences released the first batch of data on geothermal heat flow in China. It officially published four batches (1,230) of geothermal heat flow data. This provided essential support regarding parameters for evaluating geothermal resources nationwide (Wang Jiyang et al., 1988; Hu Shengbiao et al., 2001; Jiang Guangzheng et al., 2016). More than 2,000 geothermal heat flow data have been generated across the country (Pang, 2014).

In the 1980s, more than ten detailed geothermal field investigations were conducted in Tianjin, Beijing, Hebei, Shandong, Guangdong, Fujian, and Tibet. The degree of geothermal exploration was raised steadily all over China. In terms of typical areas or geological and tectonic units in China, a series of research results and monographs were produced, including Geothermics of North China (Chen, 1988), Low-medium temperature geothermal system of convective type (Wang, 1993), Geothermal Research in Oil and Gas Basins (Wang Liangshu, 1989), and others (Tong et al., 1981: Yu et al., 1981; Wang et al., 1985; Chen, 1988; Tong et al., 1989; Yu et al., 1991; Xiong et al., 1993; Chen et al., 1994; Chen et al., 1995). With the support of the State Planning Commission, the Institute of Geology of the Chinese Academy of Sciences undertook the National Geothermal Resources Research project. On the basis of the national geothermal resources survey results, combined with the research on the genesis mechanism and evaluation methods, the first evaluation of geothermal resources in China was completed. Then, the monograph *Geothermal Resources in China: Formation Characteristics and Potential Assessment* (Chen et al., 1994) and *Geothermics in CHINA* (Wang, 1996) were published. These works comprehensively describe the genetic types, distribution, and resource potential of hydro-thermal geothermal resources in China, which became the cornerstone of geothermal resource research, offering a theoretical basis for the exploration and development of regional geothermal resources.

In 1999, the Ministry of Land and Resources organized all provinces, autonomous regions, and municipalities to compile the "Plan for the Development and Utilization of Geothermal Resources in China" for the first time. As a support, an investigation was conducted to determine that there are 275 geothermal fields in China, with an annual geothermal water extraction volume of approximately 350 million cubic meters, mainly used for heating, bathing, medical treatment, tourism, breeding, planting, and other direct uses. The demand for exploration and evaluation of geothermal resources in China was analyzed, and the problems existing in exploration, evaluation, and development were summarized. (Wang et al., 2010).

2.3 The stage of integrated investigation

In 2010, the CGS, affiliated with the Ministry of Natural Resources of China, launched a new round of surveys on national geothermal resources. Based on the current investigation status and existing problems in China, a strategic roadmap for geothermal development in China was proposed. The potential of geothermal resources in China was investigated and evaluated according to three types: shallow geothermal energy, hydro-thermal resources, and HDR geothermal resources. In 2011-2015, the survey of hydro-thermal resources in 31 provinces (including autonomous regions and municipalities) across the country was completed, and the survey and evaluation of shallow geothermal energy in 336 cities above the prefecture level, on a scale of 1:50,000, were successfully carried out. The potential of HDR resources within 3 to 10 km depth has been estimated, and a total of 2,334 hot springs and 5,818 geothermal wells have been investigated. The national assessment of HDR resources has calibrated the order of magnitude of one billion tons of standard coal, which has dramatically enhanced the confidence in geothermal energy as an alternative energy source in the future.

In 2016-2022, the CGS highlighted the exploration of geothermal resources in typical areas. Two scientific and technological battles were lunched in this period, one in the Beijing-Tianjin-Hebei region focusing on hydrogeothermal resources, the other in the Gonghe Basin, Qinghai Province focusing on HDR exploration and test mining. For the first time, a comprehensive survey of shallow geothermal energy, hydro-thermal energy, and oilfield geothermal resources in the Beijing-Tianjin-Hebei region was carried out comprehensively, and multilateral utilization demonstrations were achieved. In Xiong'an New Area a high-yield geothermal reservoir above 130°C was discovered. Meanwhile, breakthroughs were made in HDR exploration in the Gonghe Basin. Geothermal exploration unveiled high-temperature HDR masses above 200°C, and experimental power generation was achieved. Through a series of systematical investigations, evaluations, and explorations, the scientific understanding of the formation mechanism of geothermal resources in China and the current conditions of geothermal resources in typical areas, such as Gonghe area, the southeast coast, and Northeast Wudalianchi pond, have significantly been improved (Lin et al., 2015; Lin et al., 2017; Lin et al., 2020; Lin et al., 2020, Zhang et al., 2019, Zhang et al., 2017).

At the same time, other relevant national departments and local government departments have also carried out effective comprehensive investigation of geothermal resources. The Ministry of Science and Technology has launched several critical research and development programs, including the National High-tech R&D Program (863 Program). In particular, Jilin University and other institutions have launched research on HDR exploration, fracturing, multi-scale and multi-field coupling mechanisms, and heat and mass transfer development. And the same time, the Institute of Geology of the Chinese Academy of Sciences assessed the potential of HDR resources in mainland China (Wang et al., 2012). The assessment results match the previous evaluation of the CGS (Lin et al., 2012). Other regions, including Tangshan in Hebei province, Datong in Shanxi province, Lijin in Shandong province, Xinghua in Jiangsu province, and Chengmai in Hainan province have also conducted deep geothermal exploration. It is worth noting that in Tianzhen County, Datong, Shanxi Province, a high-temperature and high-pressure geothermal fluid was detected at a depth of 1,624 meters, with a wellhead temperature as high as 160.2°C and a maximum flow rate of 231.15 m^3/h, achieving a breakthrough in high-temperature geothermal exploration in the central and eastern regions.

3 CHARACTERISTICS OF GEOTHERMAL RESOURCES

The geothermal resources of China is controlled by the island-arc plate-margin of the Pacific Rim and the Mediterranean-Himalayan continental-continental collisional plate-margin. The entire Chinese continental crust is divided into various fault blocks by shear fault systems of different scales and levels. In addition, faults are often favorable channels for water (hot or cold) and magmatic activities, thus becoming the main structural background controlling hydro and HDR geothermal resources, due to the co-existence of thermal and hydro-thermal resources.In the interior of the fault blocks, the thickness of crystalline basement burial and deposition is varied due to the differential movement during the formation and deformation process, and the distribution of crust and mantle directly affects the temperature of geothermal reservoirs.

Considering the occurrence of geothermal resources in different regions of China, the geothermal geological background and the conditions of the heat generation system (source), migration channel (passage), heat preservation system (cover), and seepage system (reservoir) can be summarized as "homologous symbiosis, crust and mantle generation, and tectonic heat accumulation" (Wang et al., 2020).

Accordingly, China's geothermal resources can be divided into seven sub-types: 1) sedimentary basin and ancient buried hill composite type, represented by the North China Basin; 2) sedimentary basin deep depression strata-bound type, represented by the Songliao Basin and Weihe Basin;3) fault basin geo-depression type; 4) the continental collision plate margin type, represented by the Zangdian geotropic zone; 5) the plate margin subduction zone heat-controlled structure, represented by the southeast coastal geotropic zone; 6) the uplift, represented by Tangshan Hot Spring in Jiangsu Mountainous; and 7) deep circulation and modern volcanic type, represented by Tengchong Rehai geothermal field. Affected by tectonic activities, plenty of hydro-thermal activities exist in southern

Tibet, western Yunnan province, western Sichuan province, and Taiwan, which are also the most important high-temperature hot spring-intensive belts in China. In the interior of the continent, it is dominated by medium and low-temperature geothermal resources. Uplifted mountain geothermal resources mainly include mountainous areas such as the southeast coast, Jiaodong, and Liaodong Peninsula; sedimentary basin-type geothermal resources are mainly distributed in Mesozoic and Cenozoic sedimentary basins, especially the North China Basin in the eastern region Rift basins such as the Songliao Basin, the Jianghan Basin, and the Subei Basin embraces a large amount of medium and low-temperature hot water resources (Wang et al., 2020).

3.1 Shallow geothermal resources

Shallow geothermal resources, normally developed by ground source heat pump, are widely distributed throughout China, especially concentrated in the Beijing-Tianjin-Hebei region, Shandong province, Jiangsu province, Anhui province, Henan province, Shaanxi province and parts of northeast China. The buried pipe heat pump system performs excellent suitability, with the suitable areas of the groundwater source for heat pump mainly being distributed in the eastern plain basin and areas with highly available water (Wang et al., 2017). The average burial depth of the constant temperature zone in mainland of China is generally shallower in the southeast and deeper in the northwest and northeast. In addition, the average geothermal gradient in the south is 2.45°C/100 m, while the geothermal gradient gradually increases from west to east in most parts of the north, with an average value of 3°C/100 m. The comprehensive thermal conductivity of rock and soil in most cities is 1.89~2.55W/(m·K), with the stratum structure and hydrogeological conditions being the main factors affecting the comprehensive thermal conductivity of rock and soil.

The area under survey and evaluation of shallow geothermal energy in 336 cities above the prefecture level in China, is about 170,000 square kilometers, where the annual exploitable amount is equivalent to 700 million tons of standard coal, being able to replace 1.17 billion tons of standard coal per year. The amount of coal saved is around 410 million tons per year. Shallow geothermal energy resources are mainly used for heating and cooling of buildings, and the heating and cooling area available per unit area is utilized to represent the potential of shallow geothermal energy resources. In total, 80% of the land area in those 336 cities is suitable for using shallow geothermal energy, which can allow to cool an area of 32.575 billion m^2 of buildings in summer, and heat a similar area of 32.268 billion m^2 in winter.

3.2 Hydro-thermal resources

Considering their tectonic origin, hydro-thermal resources in China can be divided into sedimentary basin type and uplifted mountain type. Dominated by geological structure, stratum lithology, magmatic activity, and other relevant factors, this distribution has obvious zonalization and regularity. For instance, sedimentary basin-type geothermal resources are mainly distributed in Mesozoic and Cenozoic plain basins in eastern China, including North China Plain, Hehuai Plain, Subei Plain, Songliao Basin, Lower Liaohe Plain, and Fenwei Basin. These basins have large reserves, thickness, and wide distribution, being considered as important geothermal resources in China (Wang et al., 2017).

Furthermore, uplift mountain type high-temperature geothermal resources are mainly distributed in southern Tibet, western Sichuan province, western Yunnan province, and Taiwan; uplift mountain type medium-low temperature geothermal resources are mainly located in mountainous and hilly areas such as the southeast coast, Jiaodong, and Liaodong Peninsula, which are also the main hot spring-intensive belts in China. In general, the proven hydro-geothermal resources are of medium and low temperature, comlemented by high temperature resources.

Geothermal resources in 15 large and medium-sized sedimentary basins are equivalent to 1.06 trillion tons of standard coal, and the annual recoverable amount is equivalent to 1.70 billion tons. Among them, the Sichuan Basin has the biggest amount of exploitable geothermal resources, equivalent to 544 million tons of standard coal, followed by the North China Plain, equivalent to 422 million tons of standard coal. High-temperature geothermal resources are mainly distributed in southern Tibet-western Sichuan-western Yunnan's intensive hydro-thermal activity zone. In those areas it is estimated that the power generation capacity of high-temperature geothermal resources is 7120 megawatts, accounting for 84.1% of the country's total of this type of resources; the power generation potential of high-temperature geothermal resources in the southeastern coastal areas is 700 megawatts, accounting for 8.27% of the country's total of those resources. Moreover, high-temperature geothermal systems are distributed in the Guanzhong Basin, the Taxkorgan region of Xinjiang Autonomous Region and the Changbai Mountain region of Jilin province.

3.3 Hot dry rock

According to the genetic type, China's HDR resources can be divided into four categories: 1) the high heat flow granite type, concentrated in the southeastern coastal areas of China; 2) the sedimentary basin type, mainly distributed in Guanzhong, Xianyang, Guide, Gonghe, the Northeast region and other acidic rocks in the lower part of the Cretaceous basins; 3) modern volcanic types, distributed in Tengchong, Changbai Mountains, Wudalianchi pond and other areas; and 4) active tectonic patterns, mainly occurring in the Qinghai-Tibet Plateau region of China, where there is local magma intrusions due to plate compression (Wang et al., 2020). Based on the selection of favorable target areas for HDR exploration, researchers followed the index weight evaluation method, thus selecting the first batch of HDR exploration target areas in China, combined with the occurrence characteristics of different types of HDR resources, including Gonghe Basin, Guide Basin, Leiqiong area, Songliao Basin, Tibet, Eastern Hebei area.

China possesses a considerable potential of HDR resources, which is a promising clean energy option in the future. Under current technical and economic conditions, the utilizable HDR are generally buried at a depth of 3-10 km. According to preliminary calculations, the total thermal energy resources in HDR at such depth in mainland China reaches 2.5×10^{25} J, equivalent to 856 trillion tons of standard coal. Considering that only 2% are exploitable resources, the production volume of HDR is around 17.2 trillion tons. The abundant resources of HDR represent the most potential strategic replacement energy, but there still are many hurdles to further mining and utilization considering the current economic and technical limitations.

4 GEOTHERMAL RESOURCES INVESTIGATION ENHANCED THE DEVELOPMENT OF GEOTHERMAL INDUSTRY

With the technical progressing and accuracy increasing of geothermal resource investigation in China, the transformation from direct utilization of geothermal water to comprehensive utilization of geothermal energy has been effectively promoted.

4.1 Hot spring surveys promoted the deployment of sanatoriums that use geothermal resources

With the intensification and widening of hot spring surveys, there was an increase in the deployment of many health spas and therapeutic installations in the country. From the mid-20th century to the 1960s, more than 600 thermal spring sanatoriums of different sizes were established across the country. According to the water mineral quality, all of these health centers can be grouped into eight categories: low mineral content spring sanatoriums (Guangdong Conghua, Yunnan Anning Beijing Xiaotangshan, and other sanatoriums), carbonated spring sanatoriums (Heilongjiang Wudalianchi Hot Spring Water Treatment Institute, Jilin Yanbian Erdaohe Thermal Spring Sanatorium, etc.), sodium chloride spring sanatoriums (Shandong Jimo, Liaoning Yingkou Xiongyue, etc.), iron spring sanatoriums (Harbin Railway Administration Wudalianchi Hot Spring Sanatorium, Gansu Tongwei Thermal Spring Sanatorium, etc.), radon spring sanatorium (Gansu Wushan Mineral Spring Sanatorium, Jilin Fushun Thermal Spring and Forestry Sanatorium for Staff, etc.), iodine spring sanatoriums (Shandong Weihai Thermal Spring Sanatorium, Liaoning Xingcheng Thermal Spring Sanatorium, etc.), sodium sulfate spring sanatoriums (Henan Ruzhou Thermal Sanatorium for Workers, Fujian Jinjishan Hot Spring Sanatorium, Gansu Qingshui Hot Spring Sanatorium for Occupational Disease Prevention and Treatment, etc.), and sodium bicarbonate spring sanatoriums (Inner Mongolia Arxan Sanatorium, Wulongbei Hot Spring Sanatorium of Shenyang Military Region, Fujian Jinjishan Thermal Spring Sanatorium, etc.). Beijing Xiaotangshan Sanatorium, established in 1988, started its exploration work in 1956, making it a national demonstration base for health management. Currently, it provides services including recuperation, health examination, and health management. Shandong Jimo Hot Spring Sanatorium was established in Qingdao in 1966, and now it is located in China Ocean Hot Spring Town. It is now a multi-functional hot spring resort and a popular destination for travel and living that provides hot spring health maintenance service and cultural experiences.

Kommentiert [1]: It was previously written as “weak spring”, which means hot spring with low mineral content. Therefore it is changed to “low mineral content spring sanatoriums”.

4.2 Geothermal water survey promoted diverse utilizations

During the geothermal survey stage that mainly focused on geothermal water exploration, more than 10 geothermal fields in several China’s provinces were studied, including Tianjin, Hebei, Guangdong, Fujian, and Tibet with detailed surveys. The significant improvement in the exploration allowed the change from resource development to energy utilization. Therefore, appeared a diversified pattern for direct uses and for electricity generation. In 1970, a pilot test for using 92°C geothermal water to generate electricity succeeded in Fengshun, Guangdong province, producing the first 86 kW of geothermal origin in China. After that, China’s first low-medium temperature geothermal power station was established, which continued in operation until the 21st century. In the 1970s, seven low-medium temperature geothermal power stations were established. Besides Fengshun, others power plants were installed in Ningxiang, Hunan province, Huailai, Hebei province, Zhaoyuan, Shandong province, Gai County, Liaoning, Xiangzhou, Guangxi Zhuang Autonomous Region, and Yichun, Jiangxi province. In 1977, China’s first high temperature geothermal power station was established in Yangbajing. Its initial capacity was 1 MWe, which was expended to 25.18 MWe in 1991, covering 50% of the power demand of the Lhasa city of Tibet at that time (Duo, 2003).

From the 1990s to the end of the 20th century, driven by the reform and opening up and the market economy, the ’thermal spring economy’ attracted more parties to geothermal exploration, transforming geothermal exploration and development from state-led to government-and-enterprise-led, which conducted the China’s geothermal industry to a sustained development. Beijing, Tianjin, Xi’an, and other provinces have successively launched comprehensive geothermal utilization, such as geothermal greenhouses, aquaculture, therapeutic bathing, and space heating, so expanding the scale of geothermal development and utilization. By the end of the 20th century, the thermal energy generated by geothermal direct uses in China reached 31 million gigajoules per year, ranking first in the world. The geothermal heating areas across China reached 15 million m^2, mainly in large and medium-sized cities such as Beijing, Tianjin, Xi'an, Zhengzhou, and Anshan, as well as in oil producing regions like Daqing in Heilongjiang province, Bazhou, Gu’an and Xiong County in Hebei province.

Kommentiert [2]: It was previously written as cubic meter and should be changed to square meter.

4.3 Integrated geothermal surveys accelerated efficient development of geothermal energy

Since 2000, the integrated geothermal surveys of shallow, hydro-thermal, and HDR resources has helped to speed up the development and utilization of geothermal energy in China. It is worth mentioning that from 2016 to 2022, CGS organized the geothermal resources survey in the Beijing-Tianjin-Hebei region and HDR exploration and experimental extraction in Gonghe basin, Qinghai Province, and made breakthroughs in deep geothermal exploration, accelerating the efficient development and utilization of geothermal energy. The total installed capacity, reported through the end of 2020, for geothermal direct utilization in China reached 40.6 GW, and the direct utilization of thermal energy reached 440 million GJ/year, accounting for 38% of the global total and ranking first in the world for 20 consecutive years. In terms of large-scale geothermal utilization, heating has become a standout. By the end of 2020, heating and cooling in a surface of 1.39 billion m^2 was supported by geothermal energy in China, with hydro-thermal resources heating 580 million m^2 and shallow geothermal resources heating and cooling 810 million m^2 (Chen, 2021). The world’s largest single clean-energy power system was built in Beijing Municipal Administrative Center. The system mainly relies on thermal energy and has supported an area of 1.5 million m^2 for heating and cooling. Tianjin employs hydro-thermal energy to heat 40 million m^2 of building area, accounting for about 7% of the city’s total building heating area. Under the impetus of the local government and Sinopec Star Company, the building heating area has reached 2.7 million m^2, accounting for 90% of the urban buildings in Xiong county, Hebei, known as Clean Heating City.

Regarding power generation with geothermal energy, several pilot and demonstration projects have been carried out in Yangyi, Tibet, Huabei Oilfield, Gonghe, Qinghai and Tianjin, etc. In 2018, the successful test operation of Yangyi Geothermal Power Plant in Tibet marked the commissioning of the world’s highest geothermal power-generating units with an altitude of 4650m and the largest single unit capacity of 16MWe in China. In 2021, the 300kW experimental geothermal ORC power plant in Tianzhen, Datong, Shanxi Province, was put into operation. In 2021, CGS successfully connected the power generated by HDR in Gonghe, Qinghai, to the national grid.

Kommentiert [3]: The reviewer asked what is the altitude and capacity of Yangyi Geothermal Power Plant. The altitude is 4650m and the capacity is 16MWe.

5 OUTLOOK

China's geothermal resources survey aims to support and serve the needs of green and low-carbon development; the survey should feature high-precision and high-resolution exploration, produce local evaluation of different regions and areas, and develop innovative and intelligent applications. The following four aspects should be the focus of the work.

(1) Strengthen the survey of nationwide geothermal resources. A national survey of the geothermal and geological condition needs to be carried out, and terrestrial heat flow needs to be measured to understand the distribution and characteristics of major geothermal reservoirs across the country. The survey should investigate and evaluate geothermal resources in three geothermal areas, namely North China, Northeast China, and the middle and lower reaches of the Yangtze River, and four geothermal zones in southeast coastal regions, Tibet and Yunnan, Ordos, and the Tan-Lu Fault, in order to determine target areas for exploration and development.

(2) Establish and improve the national geothermal exploration, observation, and monitoring system. A national geothermal resource monitoring network with high precision and high resolution, multi-field data analysis, intelligent operation and maintenance, and multi-dimensional output, should be built to provide geothermal data for the government, industry, academia, research, and the public.

(3) Map out geothermal resource zones and provide intelligent services. It is necessary to build up research on development strategies, management regulations, and technical standards of geothermal resources and promote popular science. Also, an information-based innovative service system must be built to provide solutions for geothermal development, utilization, and protection, support efficient and large-scale development and proper management of geothermal resources.

(4) Speed up platform construction and technological innovation. Drive the construction of nation-level innovation platforms for exploration and development projects of geothermal resources, HDR included. The focus should be on technical research and equipment development on geothermal reservoir formation theory, exploration, observation and monitoring, reservoir construction, efficient heat transfer, and simultaneous mineral and geothermal energy exploitation. During that, typical areas should be selected to conduct different types of geothermal exploration and extraction experiments.

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APPENDIX

Table 1: Resources of shallow geothermal energy

Province	Number of cities evaluated	Area of Evaluation (km^2)	Heating and cooling area of ground-source heating pump （100 million m^2）		Equivalence of standard coal （10,000 tons）
			Cooling in summer	Heating in winter	
Beijing	2	6130	16.02	9.59	3972
Shanghai	1	1980	4.64	14.5	5814.36
Tianjin	2	11250	12.58	13.41	3584.6
Chongqing	1	2432	21.54	38.89	675.17
Hebei	11	2460	6.35	5.99	1626.01
Shaanxi	11	2615	6.65	5.41	2762.52
Liaoning	14	9377	15.49	12.47	3743.59
Jilin	12	2985	7.43	2.85	865.76
Heilongjiang	9	2203	2.56	0.9	313.74
Jiangsu	13	26610	23.06	25.91	4699.39
Zhejiang	12	12914	8.36	8.29	1797.12
Anhui	16	11488	37.25	29.75	6353.7
Fujian	10	3411	1.28	2.11	2790.59
Jiangxi	11	2584	24.39	25.63	1313.25
Shandong	16	7936	25.81	22.87	3051.01
Henan	19	7785	11.18	12.97	2632.64
Hubei	13	5606	10.33	11.58	1290.06
Hunan	14	17012	22.77	32.67	6314.65
Guangdong	21	6735	1.98	7.36	1055.59
Hainan	3	499	0.27	0	77.98
Sichuan	21	3960	5.17	6.16	1485.65
Guizhou	10	1414	6.39	5.86	611.25
Yunnan	16	1083	1.53	1.8	304.6
Shanxi	11	5817	11.28	5.28	2801.52
Gansu	14	2130	7.13	2.48	3693.6
Qinghai	3	624	0.62	0.19	52.35
Inner Mongolia	10	2601	21.46	12.81	3222.74
Tibet	7	514	0	0.2	25.47
Guangxi	15	2942	3.35	0	1277.4
Ningxia	5	1587	3.12	1.47	574.8
Xinjiang	13	2201	5.75	3.3	1609.44
Total	336	168885	325.75	322.68	70393

Table 2: Hydro-thermal Geothermal Resource Potential (Wang et al., 2017)

Geothermal resource type	Geothermal resources of medium and low temperature					Geothermal resources of high temperature	
	Geothermal zone	Geothermal resource reserve		Recoverable heat from geothermal fluids (under recharge conditions)		Stored thermal energy /kJ)	30-year power generation potential (10^6 kW)
		Geothermal resources（kJ）	Equivalence to standard coal（t）	Minable heat（kJ/a）	Equivalence to standard coal（t/a）		
Sedimentary basin type	North China Plain	7.23E+18	2.47E+11	1.24E+16	4.22E+08		
	Hehuai Plain	5.33E+18	1.82E+11	9.02E+15	3.08E+08		
	Subei Plain	6.75E+17	2.30E+10	9.20E+14	3.14E+07		
	Songliao Basin	1.24E+18	4.22E+10	2.01E+15	6.87E+07		
	Lower Liaohe Basin	3.95E+16	1.35E+09	7.52E+13	2.56E+06		
	Fenwei Basin	2.20E+18	7.49E+10	3.86E+15	1.32E+08		
	Ordos Basin	1.48E+18	5.03E+10	2.68E+15	9.15E+07		
	Sichuan Basin	9.62E+18	3.28E+11	1.59E+16	5.44E+08		
	Jianghan Basin	2.49E+17	8.51E+09	3.64E+14	1.24E+07		
	Hetao Basin	6.61E+17	2.25E+10	9.59E+14	3.27E+07		
	Yinchuan Basin	9.37E+17	3.20E+10	1.43E+15	4.88E+07		
	Xining Basin	1.34E+17	4.57E+09	2.09E+14	7.12E+06		
	Total	2.98E+19	1.02E+12	4.98E+16	1.70E+09		
Uplifted mountain type	Southern Tibet - Western Sichuan - Western Yunnan	3.16E+17	1.08E+10	7.22E+13	2.46E+06	3.37E+17	712
	Southeast coastal area	1.71E+17	5.85E+09	6.44E+13	2.20E+06	3.56E+16	70
	Jiaoliao Peninsula	2.69E+14	9.18E+06	2.54E+12	8.68E+04		
	Taiwan			1.88E+13	6.42E+05		
	Total	4.88E+17	1.67E+10	1.58E+14	5.40E+06	3.72E+17	782

Table 3: Hot dry rock at a depth of 3-10 km in China's continental area (Wang et al., 2017)

Number	Calculated horizon depth /km	Hot dry rock reserves		The minable volume of hot dry rocks (extractable at 2%)	
		Resource volume/J	Equivalence to standard coal / trillion tons	Resource volume/J	Equivalence to standard coal / trillion tons
1	3.0—4.0	1.9×10^{24}	64.8	3.8×10^{22}	1.3
2	4.0—5.0	2.5×10^{24}	85.3	5×10^{22}	1.71
3	5.0—6.0	3×10^{24}	102	6×10^{22}	2.05
4	6.0—7.0	3.6×10^{24}	123	7.2×10^{22}	2.46
5	7.0—8.0	4.2×10^{24}	143	8.4×10^{22}	2.87
6	8.0—9.0	4.7×10^{24}	160	9.4×10^{22}	3.21
7	9.0—10.0	5.3×10^{24}	181	1.06×10^{23}	3.62
3.0~10.0 km		2.52×10^{25}	856	5.04×10^{23}	17.2

hydro-geothermal