INTRODUCTION

As the global population continues to grow, the environmental pollution and exhaustion of nonrenewable energy are getting more and more hazardous. At present, many countries actively develop and apply new and renewable energy sources to reduce their dependence on fossil fuels. This problem also exists in China, where about 64.3% of electricity in 2016 was produced by coal-fired power plants. In 2017, the renewable energy power generation worldwide increased by 6.3% (380 TWh),
and renewable energy accounted for 25% of the global electricity generation. The variation of power generation sources in 2016-2017 and their breakdown in 2017 are shown in Figure 1A,B, respectively. The rapid global development of renewable (mainly, wind and solar) energies is observed. Trends concerning major types of renewable energy (global installed capacity) in 2007-2017 are illustrated in Figure 2.

Geothermal resources provide green, low-carbon, and renewable clean energy, with abundant reserves and massive potential for application. The exploration and development of geothermal resources have promoted their further utilization, which was mainly reduced to their direct applications for heating, breeding, and industrial purposes. Noteworthy is that in 2015, the annual direct production capacity of geothermal energy in the world reached 70,885 MW. A modern alternative to the direct usage of geothermal resources is geothermal power generation, where geothermal resources, namely underground hot water, steam, and hot dry rock (HDR), are used as power sources. The advantages of geothermal power generation include (a) continuous (24 hours per day) electricity generation, (b) stable and predictable supply, in contrast to solar and wind energies, (c) clean and sustainable production, and (d) reduction of CO2 emission. In 1904, the first dry steam geothermal power station was constructed at Larderello, Italy, due to efforts of Italian inventor Conti, who opened a new chapter in the geothermal utilization. In recent decades, the geothermal power generation exhibited an accelerated growth: Its global installed capacity increased from 6832 MW in 1995 to 14,600 MW in 2018. The global installed capacity variation from 1950 to 2018 is depicted in Figure 3.

The use of geothermal resources in China has a long history, but the actual large-scale exploration and development

**FIGURE 1** (A) The variation of power generation sources in 2016-2017; (B) electricity generation sources in 2017

**FIGURE 2** Trends in development of renewable energy sources (installed capacity) in 2007-2017
began only in the 20th century, including a large-scale geothermal exploration and hot water utilization, which were scientifically substantiated by the Chinese Academy of Sciences, in particular, by Li Siguang, the founder of China’s geomechanics.8 China's geothermal resources account for about 8% of the global geothermal energy reserves but are unevenly distributed, with apparent regularity and regionality.9 High-temperature geothermal resources are mainly located in southern Tibet, western Sichuan, western Yunnan, and Taiwan, while low-and medium-temperature ones are mostly distributed in large-scale sedimentary basins and mountainous fault belts.10,11 Noteworthy is that China has abundant HDR resources, which is assessed as \(2.52 \times 10^{25}\) J and is equivalent to \(85.6 \times 10^5\) billion tons of standard coal.12 The exploration of HDR resources is lucrative and meets the strict requirements of the national clean energy development and sustainability strategy.

For decades, the low-temperature geothermal resources in China were directly utilized, but the geothermal power generation is still in its infancy. Cities such as Beijing and Tianjin have achieved excellent results in the use of geothermal water heating and industrial heat, and China’s annual production capacity of directly used geothermal heat is the best in the world.13-15 In 1970, China built its first geothermal power station in Fengshun, Guangdong Province, and then constructed seven medium- to low-temperature geothermal power stations, including Huitang in Ningxiang County, Hunan province; Houhaoyao in Huailai County, Hebei Province; and Tang Dongguan in Zhaoyuan County, Shandong Province.16,17 The first high-temperature geothermal power station was launched in Yangbajing, Tibet, in 1977.18 Currently, only Yangbajing, Fengshun, and Huabei Oilfield geothermal power stations are still in operation, whereas Yangyi geothermal power stations are under construction.19 At present, China’s total installed capacity is approx. 27.78 MW, ranking 18th in the world.6

Given the environmental impacts and benefits, an enhanced geothermal system (EGS) is considered as one of the most lucrative technologies for the large-scale generation of electric power.4 China is rich in HDR resources, which can be cost-effectively developed via the EGS technology. However, the EGS implementation in China (even as a pilot project) is quite challenging due to pending problems of a proper site selection, land suitability and availability, high investment risks, and induced seismic activity. For the EGS system implementation, the main stumbling block is the required formation of artificial underground geothermal reservoirs,20 which is currently ensured by hydraulic fracturing using polyallylamine and supercritical CO₂ as fracturing fluids.21,22 The main geothermal power generation technologies include dry steam, flash, and binary cycle technologies. These technologies were permanently optimized by international experts, which also introduced breakthrough solutions, such as double-flash (DF), flash-organic Rankine cycle (FORC), and double-flash-organic Rankine cycle (DFORC). At present, the most widely used is flash technology, which accounts for 62% of the global installed capacity. However, DFORC power plants also look very promising for the utilization of low-temperature geothermal resources.23 The cascade utilization of geothermal resource can increase the thermal efficiency of the system and maximize the geofluid usage.23 Geothermal resources can also be combined with other energies to form a hybrid power generation system such as (a) solar-geothermal, (b) oil-geothermal, and (c) geothermal mine systems.

The rest of this paper is organized as follows. Section 2 discusses the distribution of geothermal resources in China and the assessment of shallow geothermal, hydrothermal geothermal, and HDR resources. This survey of available economic reports and technological solutions makes it possible to reveal the latest trends in the geothermal power generation in China. Section 3 discusses the geothermal power generation (dry steam, flash, and binary cycle) technologies, as well as enhanced geothermal system (EGS), which are linked to their lucrative implementation sites in China. Section 4 discusses the prospects of low-cost/large-scale geothermal power generation, such as low-medium temperature, solar-geothermal hybrid, and geothermal mine power generation, with a strong indication of EGS advantages. The biased distribution of power consumers in China and its effect on the further development of power plants are analyzed in Section 5. Based on the revealed trends of geothermal resource development in China, several guidelines are recommended in Section 6, whereas the study is concluded in Section 7.

2 GEOTHERMAL RESOURCES IN CHINA

2.1 Distribution of geothermal resources

The global distribution of high-temperature geothermal resources is heterogeneous and is mainly concentrated within
a narrow zone of the tectonic plate margin. According to its geographic distribution and the mechanical properties of the plate interface, it can be subdivided into four large-scale tropical zones: (a) Circum Pacific geothermal belt, (b) Atlantic mid-ocean ridge geothermal belt, (c) Red Sea-Gulf of Aden-East African Rift Valley geothermal belt, and (d) Mediterranean-Himalayan geothermal belt. The global geothermal belts and plate tectonics are depicted in Figure 4.

The distribution of geothermal resources is closely related to the geological tectonic activity. The high-temperature geothermal resources are located in the marginal zone of the plate with an abnormal tectonic activity (eg, Himalayan and Taiwan geothermal belts). The low- and medium-temperature geothermal resources are mostly located in uplifted mountain-type and sedimentary basin areas within the plates. According to the formation and distribution characteristics of geothermal resources, they can be subdivided into (a) plate margin and (b) intraplate geothermal resources. Table 1 shows the geologic structure, background, fluid temperature, heat source, and representative geothermal areas and fields of each geothermal resource.

China has abundant geothermal resources with the thermal value of $3.06 \times 10^{18}$ kWh per year, accounting for about 8% of the global geothermal energy reserves. However, low-temperature geothermal resources prevail over high-temperature ones. The distribution map of geothermal resources in China is depicted in Figure 5. The high-temperature geothermal belt is mostly distributed in the Mediterranean-Himalayan and West Pacific island-arc geothermal belts, including southern Tibet, western Sichuan, western Yunnan, and Taiwan. The low- and medium-temperature geothermal fields are located all over the country and mainly distributed in large-scale sedimentary basins, the geothermal belt in the southeast, and Jiaoliao, including the southeast coast, eastern, and northeastern China. The geothermal resources of large-scale sedimentary basins have the characteristics of right storage conditions, multiple reservoirs, large thickness, and wide distribution, which implies that these regions have the most significant development potential for geothermal resources. In contrast, geothermal resources distributed in mountain fault zones are generally quite small in scale.

### 2.2 | Assessment of geothermal resources

#### 2.2.1 | Shallow geothermal resources

Shallow geothermal energy refers to low-temperature geothermal resources with a temperature below 25°C in the shallow crust, groundwater, and surface water under the current technological and economic conditions within a depth of 200 m below the surface. At present, shallow geothermal energy is mainly utilized via heat pump systems consisting of a groundwater source, buried pipe, and ground source to extract heat for urban winter heating and summer cooling. According to the 2015 survey and evaluation results of the China Geological Survey of the Ministry of Land and Resources of China, the heat capacity of shallow geothermal energy (within a depth of 200 m or less) in 336 cities at prefecture level and above is $1.11 \times 10^{17}$ kJ°C. The annual recoverable resources are equivalent to 700 million tons of standard coal, replacing 1.17 billion tons/y of standard coal and saving 410 million tons of coal per year. The calculated values of the heat capacity and heat transfer rate of shallow geothermal resources are listed in Table 2.

#### 2.2.2 | Hydrothermal geothermal resources

Hydrothermal geothermal resources are widely distributed and abundant in China. They can be used for power generation, heating, industrial utilization, medical treatment, bathing, and breeding. Hydrothermal geothermal resources are classified by temperature and can be subdivided into three levels, namely (a) high-temperature ones (warmer than 150°C), (b) medium-temperature ones (90-150°C), and (c) low-temperature ones (colder than 90°C). The two latter types (ie, medium-low temperature) of geothermal resources are mainly distributed in 15 large- and medium-sized sedimentary basins/plains, such as Sichuan Basin, North China Plain, Hehuai Plain, Northern Jiangsu Plain, Songliao Basin, Lower Liaohai Plain, and Yanqi Basin. Table 3 shows the medium- to low-temperature geothermal resources of the main sedimentary basins. The geothermal resources in 15 sedimentary basins/plains are equivalent to 1060 billion tons of standard coal. Noteworthy is that 30.9% of these resources are concentrated in the Sichuan Basin, while the North China Plain and the Hehuai Plain account for 23.3% and 17.2%, respectively. Table 3 shows the contribution of plains (basins) to the total geothermal resources of China. High-temperature geothermal resources are mainly located in the southern Tibetan-western Sichuan-western Yunnan, southeastern coastal areas, the Jiaoliao Peninsula, and Taiwan's hydrothermal activity-intensive belts.

#### 2.2.3 | Hot Dry Rock (HDR) resources

The high-temperature rock mass, which is buried more than 1 km below the ground surface, is generally warmer than 200°C and has zero or low percentage of the internal fluid. It is referred to as hot dry rock (HDR) and is a very lucrative geothermal resource. With the progress of HDR
development and utilization technologies, especially the advancement of fracturing technology and the reduction of costs, the temperature limit of HDR resources is gradually blurred. HDR geothermal resources are distributed worldwide and treated as a breakthrough solution to the growing energy demands. Due to the impact of collisions between the Asia‐Europe plate, the Pacific plate, and the Indian Ocean plate, China’s geothermal analysis shows that the southern area is stronger than the northern one, while the southeast coastal and Tibetan Plateau tropical zones are the most prominent. Affected by the Pacific plate, a high-temperature tropical zone has formed in Changbai Mountain, Wudalianchi, Beijing, Tianjin, and Shandong Peninsula. In 2017, within the framework of the HDR exploration project of the Gonghe Basin in Qinghai, jointly organized by the China Geological Survey and the Ministry of Land and Resources of Qinghai Province of China, the shallowest (3705 m deep) and highest temperature (236°C) HDR mass was drilled in the Gonghe Basin. This domain is rich in geothermal resources with a high calorific value, which makes it lucrative for the further implementation of HDR pilot projects.

China National Geological Survey’s “National Demonstration Project for Evaluation of Hot Dry Rock Resource Potential” constructed the map of heat distribution in mainland China (Figure 6) based on 938 heat flow data. It represents the geothermal field and is instrumental in the deep drill temperature calculation. As seen in Figure 6, the overall spatial distribution trend of geothermal flow can be summarized as follows: “high in the south and low in the north” in the west, “high in the east and low in the west” in the east, and “high in the north and low in the south” in the middle. In 2016, Jiang et al released the fourth edition of the geothermal heat data compilation for mainland China. As compared to the third edition, 368 new heat flux data were added, and the total number reached 1230. The new heat flow data improved the low coverage of geothermal data in China and filled the gaps in heat flow measurement in Tibet, Ngari Prefecture, Guizhou Province, Guangxi Province, and Jilin Province.

Figure 7 shows deep temperature patterns in the continental area of China. Temperature is the most essential criterion of the existence or absence of HDR resources. As the ground temperature rises with depth, according to the definition, the distribution of HDR is widespread, as long as it reaches a certain depth to meet the HDR conditions. In general, the temperature of the crust in the southern part of China is the highest in the mainland, relatively high in the west of Yunnan and the entire eastern part (south China, north China, and northeast). Meanwhile, the temperature of the Junggar Basin, Tarim Basin, Qaidam Basin, and Inner Mongolian Yinshan Mountains is comparatively low.

Wang et al used the volume method and Geographic Information System (GIS) software to estimate the reserves of HDR resources in China’s land areas based on the calculated 3.5-9.5km-deep temperature data. The estimated results are shown in Table 4. The reserve of HDR resources is $2.52 \times 10^{25}$ J, which is equivalent to $85.6 \times 10^5$ billion
Noteworthy is that, according to 2% of recoverable resources, this is 3927 times higher than China's current total energy consumption, which in 2016 corresponded to 4.36 billion tons of standard coal\textsuperscript{44). Somewhat lower estimates were made by Wang et al,\textsuperscript{34} which implied that the total HDR resources in China located within the depth range from 3 to 10 km amounted to $2.09 \times 10^{25}$ J, which was equivalent to 71.49 $\times 10^5$ billion tons of standard coal. Despite some discrepancies in these estimates,\textsuperscript{34,43} they strongly indicate that China has an abundant reserve of HDR resources, in which exploration is lucrative and meets the requirements of the national clean energy development and sustainability strategy.

3 | DEVELOPMENT OF INNOVATIVE GEOTHERMAL POWER GENERATION TECHNOLOGIES

3.1 | Overview of geothermal power generation in China

Geothermal power generation uses geothermal resources (underground hot water, steam, and HDR) as power sources, in which thermal energy is first converted into mechanical energy and then into electricity. Geothermal power has been rapidly developed in recent years. The total installed capacity of geothermal power in the world has increased from 6832 MW in 1995 to 14 600 MW by the end of 2018 and is expected to reach 21 443 MW in 2020.\textsuperscript{6,7} The prevailing share of installed capacity corresponds to the US and Asia-Pacific region. The United States has the most abundant geothermal resource reserves, the most substantial geothermal energy development, and the highest geothermal power generation in the world (the installed capacity in 2018 was 3639 MW), following by Philippines (1948 MW) and Indonesia (1868 MW). Iceland is a model of global geothermal development (755 MW). About 1/3 of the electricity generation comes from geothermal power generation, and geothermal energy accounts for 69% of primary energy.\textsuperscript{45} Table 5 shows the changes in the installed capacity of geothermal power in several countries from 1995 to 2018.

Geothermal power generation in China started in the early 1970s, which coincided with the oil crisis triggering the development and utilization of alternative energy sources worldwide. In 1970, China’s first geothermal power station (92°C, 300 kW) was built in Dengwu, Fengshun County, Guangdong Province. China became the eighth country to achieve geothermal power generation. In 1971, the first organic medium- to low-temperature geothermal power station (67°C, 50 kW) was built in Wentang, Yichun County, Jiangxi Province, which maintains the lowest temperature geothermal power generation record so far.\textsuperscript{17} Subsequently,
five low- and medium-temperature geothermal power stations were successfully constructed (see Figure 8): Huitang, Ningxiang County, Hunan (92°C, 300 kW); Houhaoyao, Huailai County, Hebei (79°C, 200 kW); Tang Dongguan, Zhaoyuan County, Shandong (91°C, 200 kW); Yingkou, Liaoning (75°C, 100 kW); and Reshui, Xiangzhou city, Guangxi (73°C, 200 kW). The medium- to low-temperature geothermal power stations were technically feasible at the time, but not economically viable and cost-effective. Therefore, at the end of the 1970s, except for Dengwu and Huitang, the remaining five medium- to low-temperature geothermal power stations were suspended.

The first high-temperature geothermal power station was built in Yangbajing, Tibet, in 1977. The initial installed capacity was only 1000 kW. After that, eight new units (3 MW each) were added successively from 1981 to 1991. In 2009 and 2010, two new sets of screw expansion generators (with an installed capacity of 2 MW) have been put into operation, respectively. The total installed capacity has reached 26.18 MW, whereas the original 1000-KW units have been discontinued. This power station has achieved excellent economic benefits in the past few decades of operation and contributed to 50% of Lhasa’s summer power supply and 60% of winter power supply. In addition to Yangbajing, two more power stations were launched in Tibet Langjiu (103-105°C, 2 MW) and Naqu (95-114°C, 1 MW). However, the operation of these power stations was suspended due to their low power generation efficiency, poor economic efficiency, and scaling problems. In 2018, China’s Tibet Yangbajing (26.18 M), Yangyi (0.9 MW), Guangdong Dengwu (0.3 MW), and Huabei Oilfield (0.4 MW) geothermal power stations, with the total installed capacity of 27.78 MW, were in operation.

The Yangyi high-temperature geothermal power station was the large-scale implementation of geothermal resources’ using screw expansion power machines. In September 2011, a full-flow 400-kW screw expander power generation test unit was installed at the power station (Figure 9A). Based on the successful operation of this unit, a 500-kW container-type screw expansion generator prototype was developed and installed in August 2012 (Figure 9B). The designed total installed capacity of the power station (32 MW) was implemented in two phases (16 MW per phase) and reached its expected maximum in 2018.

The utilization of medium- to low-temperature geothermal sources necessitated the implementation of innovative technology, called “organic Rankine cycle” (ORC), which applied organic high-molecular-mass fluids with a liquor-vapor phase change (boiling point) occurring at a lower temperature.
| Evaluation area/km² | City       | Summer cooling BPHPS HTR/KW | Winter heating BPHPS HTR/KW | Summer cooling GSHPS HTR/KW | Winter heating GSHPS HTR/KW | Summer cooling GWHPS HTR/KW | Winter heating GWHPS HTR/KW | Summer cooling | Winter heating |
|---------------------|------------|-----------------------------|----------------------------|-----------------------------|----------------------------|----------------------------|-----------------------------|----------------|----------------|
| 6.24                | Qinghai    | 2.68 × 10^6                 | 1.40 × 10^6                 | 6.73 × 10^6                 | 4.35 × 10^6                 | 2.27 × 10^6                 | 1.08 × 10^6                 | 7.62 × 10^5    | 4.35 × 10^5    |
| 2.10                | Tibet      | 0                           | 0                           | 2.07 × 10^6                 | 1.51 × 10^6                 | 5.86 × 10^6                 | 3.57 × 10^6                 | 4.35 × 10^5    | 3.57 × 10^5    |
| 2.60                | Hohhot     | 6.56 × 10^6                 | 4.35 × 10^6                 | 2.04 × 10^6                 | 1.39 × 10^6                 | 8.39 × 10^6                 | 5.76 × 10^6                 | 4.35 × 10^5    | 3.57 × 10^5    |
| 2.60                | Inner Mongolia | 4.49 × 10^6                 | 3.57 × 10^6                 | 2.52 × 10^6                 | 1.45 × 10^6                 | 3.55 × 10^6                 | 2.03 × 10^6                 | 4.35 × 10^5    | 3.57 × 10^5    |
| 2.00                | Sinkiang   | 1.51 × 10^6                 | 1.39 × 10^6                 | 2.35 × 10^6                 | 1.45 × 10^6                 | 5.94 × 10^6                 | 3.57 × 10^6                 | 4.35 × 10^5    | 3.57 × 10^5    |
| 2.00                | Heilongjiang | 3.57 × 10^6                 | 2.03 × 10^6                 | 6.70 × 10^6                 | 4.35 × 10^6                 | 7.90 × 10^6                 | 5.76 × 10^6                 | 4.35 × 10^5    | 3.57 × 10^5    |
| 2.60                | Jiangsu    | 2.03 × 10^6                 | 1.39 × 10^6                 | 5.76 × 10^6                 | 3.57 × 10^6                 | 8.39 × 10^6                 | 5.76 × 10^6                 | 4.35 × 10^5    | 3.57 × 10^5    |
| 2.50                | Zhejiang   | 3.57 × 10^6                 | 2.03 × 10^6                 | 6.70 × 10^6                 | 4.35 × 10^6                 | 8.39 × 10^6                 | 5.76 × 10^6                 | 4.35 × 10^5    | 3.57 × 10^5    |
| 2.50                | Guangdong  | 4.35 × 10^6                 | 2.03 × 10^6                 | 6.70 × 10^6                 | 4.35 × 10^6                 | 8.39 × 10^6                 | 5.76 × 10^6                 | 4.35 × 10^5    | 3.57 × 10^5    |
| 2.50                | Guangxi    | 3.57 × 10^6                 | 2.03 × 10^6                 | 6.70 × 10^6                 | 4.35 × 10^6                 | 8.39 × 10^6                 | 5.76 × 10^6                 | 4.35 × 10^5    | 3.57 × 10^5    |

**Abbreviations:** BPHPS, buried pipe heat pump system; GSHPS, ground-source heat pump system; GWHPS, groundwater source heat pump system; HTR, heat transfer rate.
than the water-steam phase change. The low-temperature heat is converted to useful work and electricity.

The world’s first medium- to low-temperature-associated geothermal power station was launched in 2006 in the Teapot Dome oil field in northern Wyoming, USA. The installed power of this station with the ORC circulation principle was 250 kW. The second oilfield-associated geothermal power station (400kW) was constructed in 2011, in the Huabei Oilfield of China. The operating parameters are detailed in Table 6. The expected power generation capacity of the power station is 1.5 million kW·h per year, with an average annual oil increase of 120,000 tons. It saves 4100 t of fuel per year and reduces CO2 emissions by 26,000 t/a. In 2017, Yang et al. conducted the experimental study of geothermal power generation using abandoned oil wells and experimentally verified ORC geothermal power generation methods. Figure 10 shows the schematic diagram and the experimental layout of the geothermal ORC system with the working medium of pentafluoropropane (R245fa). The system consists of six main sections: geothermal water cycle, intermediate water cycle, ORC, cooling water cycle, lubricant oil cycle, and bypass and control systems.

The experimental results obtained strongly indicate that the turbine efficiency of 78.52% and ORC efficiency of 5.33% could be reached. This combination of ORC principle with oil-geothermal power generation can reduce exploration risks and upfront drilling investments. Besides, geostress fields can be developed for testing geothermal equipment and geothermal power plants, where mechanical, thermal, and mineral energy can be utilized. The oil-field area is rich in geothermal resources and geological data, and contains numerous abandoned wells. Therefore, it has a vast geothermal energy utilization market. Li et al. analyzed the efficient development and utilization of associated geothermal energy in the oilfield, in particular, the prospects of geothermal power generation. The above model is considered very lucrative for the development of such large oilfields as Daqing, Shengli, and Liaoh in China.

3.2 | Geothermal power generation technology

3.2.1 | Dry steam technology

Dry steam power generation technology transfers steam extracted from geothermal production wells to turbines, where it produces useful work and drives generators to produce electricity. Insofar as dry steam technology requires high steam quality, solid impurities (≥10 μm) and some gases (CO2, H2S, NH3, etc) in the steam, before entering the engine, must be separated to reduce the wear and corrosion of the steam turbine. Dry steam technology has the characteristics of mature technology, simple process, safety, and reliability, and is the primary form of geothermal power generation. According to Ruggero Bertani’s statistics for 2016, the installed capacity of dry steam power generation systems accounts for 23% of the global amount. In 2014, there were 63 dry steam geothermal power plants worldwide, mainly in the United States, Italy, Indonesia, and Japan. A schematic diagram of a dry steam power generation system is depicted in Figure 11A.

3.2.2 | Flash technology

When the geothermal fluid in the reservoir is a liquid-gas mixture, the flash (also known as expansion steam power generation) technology can be used to generate electricity. First, the steam and water mixture output from the production well with a particular pressure is split into steam and hot water in a steam separator. Steam is sent to a steam turbine or other thermal power generators to generate electricity, while separated geothermal water can be used for double-flash or direct recharge well production depending on the pressure. When the double-flash is performed, separated geothermal water enters the flash evaporator for the secondary separation, gets partly converted into the secondary steam with lower pressure, and is transferred to the low-pressure section of the steam turbine. Flash technology is often applied when the geofluid temperature exceeds 150°C. However, the system operation and maintenance complexity increase with the number of flash stages, so that the double-flash technology is mainly used for high-temperature resources (>250°C). The double-flash power plant was reported to produce by 15%-25% more power than a single-flash one under the same geothermal fluid conditions. Triple-flash technology also found applications in the United States, New Zealand, Turkey, and other countries. Figure 11B shows the schematic diagram of the single- and double-flash system.

3.2.3 | Binary cycle technology

The binary cycle system consists of two closed-loop circulation subsystems containing (a) geothermal fluid and (b) organic working fluid. The geothermal water through heat exchanger transfers heat to the working fluid with a lower boiling point, which is heated to the dehydrated (dry) steam state. The working medium steam enters the power machine to do useful work and then drives the generator to produce electricity. The organic working fluid steam of residual work is reduced to the liquid state in the condenser and can be recycled, while geothermal water is pumped back into the geothermal well. Binary cycle systems commonly use such organic media as hydrocarbon and fluorocarbon, ISO alkane with a boiling point at normal pressure of −11.7°C, butane (−0.5°C), propane (−42.17°C), Freon, and others. Regarding the
selection of working fluids, Hung et al analyzed the effects of several working fluids such as benzene, R11, R12, R134a, and R113 on the ORC process. \[57,58\] Guo et al investigated 27 fluids using three screening criteria, which revealed the best overall performance of E170, R600, and R141b fluids. \[59\] The choice of organic working media has a critical effect on the operating cost and power generation efficiency of geothermal power stations. Since most organic media are toxic, flammable, and explosive, the circulatory system should be leak- and waterproof. The schematic diagram of a double-cycle power generation system is shown in Figure 11C.

The selection of particular technology to be used in geothermal power plants should be based on the conditions of geothermal resources: The binary cycle system is applied to lower-temperature ones (usually below 150°C), while the flash and dry steam power generation systems are applied to higher-temperature ones (above 150°C), where they exhibit higher power generation efficiency and economic benefits.

### Enhanced Geothermal Systems (EGS)

The enhanced geothermal system (EGS) is a system that extracts heat economically from low-permeability and low-porosity high-temperature rock formations (hot dry rock). \[60\] The system consists of two parts: the ground power generation system and the underground heat exchange system. The main steps for the development of EGSs are as follows: (a) resource exploration and assessment; (b) drilling of production/reinjection wells; (c) creation of a reservoir; (d) the injection/production cycle for extracting heat; (e) power plant operation; and (f) maintenance of the reservoir. \[61\] Figure 12 shows the schematic diagram of the EGS.

China's large-scale research on the EGS started in 2000 when the research team of Prof. Zhao \[62\] addressed the geothermal development of high-temperature rock masses and successfully implemented several HDR-related technologies. In 2007, the China Energy Research Association geothermal professional committee signed a cooperation agreement with the Petratherm Company (Australia) to jointly undertake the research on the resource potential of enhanced geothermal systems in China and concluded the study in October 2009. \[63\] In 2012, the National High-Tech Research and Development Program (#863) launched the “Research on key technologies of development and comprehensive utilization of thermal energy in HDR.” In June 2016, Fujian Xianghe Geothermal Development Co., Ltd. launched a 5 billion yuan (784 mlm USD) investment into the HDR-based EGS pilot project to develop a comprehensive utilization of waste heat energy, with the accelerated growth of geothermal power generation. \[64\] However, the current status of China’s EGS is far from the industrial implementation stage. Although many scientific research institutes of China conducted theoretical and experimental studies with lucrative results in this area, the EGS pilot research base has not yet been established. Since the pilot project was aimed to verify and improve the performance of the available EGS technology, reduce the construction and

### Table 3 Evaluation of moderate- and low-temperature geothermal resources of main sedimentary basins

| Name                | Resources/KJ | Equivalent to standard coal/Billion tons | Percentage/ % | Recoverable resources/KJ | Equivalent to standard coal/Billion tons | Percentage/ % |
|---------------------|--------------|-----------------------------------------|---------------|----------------------------|-----------------------------------------|---------------|
| North China Plain   | 7.23 × 10^18 | 2470.0                                   | 23.3          | 1.46 × 10^18               | 498.00                                  | 27.7          |
| Huai River Plain    | 5.33 × 10^18 | 1820.0                                   | 17.2          | 9.20 × 10^17               | 314.00                                  | 17.4          |
| Northern Jiangsu Plain | 6.75 × 10^17 | 230.0                                   | 2.2           | 1.52 × 10^17               | 51.90                                   | 2.9           |
| Songliao Basin     | 1.24 × 10^18 | 422.0                                   | 4.0           | 1.24 × 10^17               | 42.20                                   | 2.3           |
| Lower Liaohe River Plain | 3.95 × 10^16 | 13.5                                    | 0.1           | 3.95 × 10^15               | 1.35                                    | 0.1           |
| Fenwei Basin       | 2.20 × 10^18 | 749.0                                   | 7.1           | 4.38 × 10^17               | 149.00                                  | 8.3           |
| Ordos Basin        | 1.48 × 10^18 | 503.0                                   | 4.7           | 2.11 × 10^17               | 72.00                                   | 4.0           |
| Sichuan Basin      | 9.62 × 10^18 | 3280.0                                   | 30.9          | 1.44 × 10^18               | 493.00                                  | 27.4          |
| Jianghan Basin     | 2.49 × 10^17 | 85.1                                    | 0.8           | 4.99 × 10^16               | 17.00                                   | 0.9           |
| Hetao Basin        | 6.61 × 10^17 | 225.0                                   | 2.1           | 1.65 × 10^17               | 56.40                                   | 3.1           |
| Yinchuan Basin     | 9.37 × 10^17 | 320.0                                   | 3.0           | 2.32 × 10^17               | 79.10                                   | 4.4           |
| Xining Basin       | 1.34 × 10^17 | 45.7                                    | 0.4           | 1.34 × 10^16               | 4.57                                    | 0.3           |
| Junggar Basin      | 4.78 × 10^17 | 163.0                                   | 1.5           | 2.39 × 10^16               | 8.16                                    | 0.5           |
| Tarim Basin        | 4.83 × 10^17 | 165.0                                   | 1.6           | 2.42 × 10^16               | 8.26                                    | 0.5           |
| Quidam Basin       | 3.04 × 10^17 | 104.0                                   | 1.0           | 3.04 × 10^16               | 10.40                                   | 0.6           |
| **Total**          | 3.11 × 10^19 | 10 600.0                                 |               | 5.29 × 10^18               | 1800.00                                 |               |
operating costs of the future EGS projects, and realize its final commercial deployment, its realization is urgent. At present, EGS pilot projects are underway in Australia, France, Germany, Japan, Korea, the United States, and the UK, so the competition in this domain is also quite challenging. The distribution of global EGS sites is depicted in Figure 13.

Multiple scholars addressed the issues of improving the geothermal power generation efficiency by either optimizing the operating conditions or modifying the existing power generation systems. Li and Lior studied and compared the performance of six geothermal power generation systems of the EGS power station (with the temperature range of geothermal fluid from 200 to 800°C). Luo et al. and Huang conducted the thermodynamic analyses of different types of geothermal power generation systems, which revealed that ORC plants exhibited higher power generation efficiency when the fluid temperature was lower than 130°C, while the higher temperature was more appropriate for flash-type power plants. Zhu et al. analyzed in detail the thermodynamic properties of four geothermal power generation systems, which are depicted in Figure 14: single-flash (SF), double-flash (DF), flash-organic Rankine cycle (FORC), and double-flash-organic Rankine cycle (DFORC). The results obtained provided a reference for the selection of the most appropriate power generation system for the EGS and outlined reasonable temperature and steam dryness ranges for each power generation system.

As seen in Figure 14, when the fluid temperature is lower than 170°C, the FORC system has the best thermodynamic performance. The DF system is suitable for fluid temperatures exceeding 170°C, in case the steam dryness is below 0.2. When the fluid dryness exceeds 0.2, both DF and DFORC systems can be selected, whereas DFORC exhibits a better performance than DF at lower temperatures.

4 | THE ROADMAP OF GEOTHERMAL POWER DEVELOPMENT AND UTILIZATION

4.1 | Low-cost and large-scale geothermal power generation

4.1.1 | Medium- to low-temperature geothermal power generation

In China, the medium- to low-temperature geothermal resources prevail over the high-temperature ones but mainly involve direct utilization. The respective average energy utilization efficiency is about 30%, which is far lower than that of geothermal power generation (73%). On the other hand, the installed capacity of geothermal power generation in China is 27.78 MW, of which the contribution of high-temperature geothermal power plants is about 97% (or 27.08 MW in Yangbajing, Yangyi) versus 3% of
medium-low ones (0.7 MW in Huabei Oilfield, Dengwu). The latter type of resource has abundant reserves and wide application prospects. Therefore, promoting China’s low-cost, large-scale development of medium- to low-temperature geothermal power generation is crucial. In 2017, the “Thirteenth Five-Year Plan for Geothermal Energy Development and Utilization” jointly issued by the National Development and Reform Commission, the National Energy Administration, and the Ministry of Land
and Resources of China explicitly stated that through government guidance, private and state enterprises aimed at the low-temperature geothermal power generation would be established in Hebei, Tianjin, Jiangsu, and other eastern regions of China. It can be seen that the country has a strategic deployment in this area. The next step is to focus on technological breakthroughs, increase the scale of application, and reduce the construction and operating costs.

4.1.2 | Solar-geothermal Hybrid (SGH) power generation

Many of the world’s high-quality solar energy are consistent with the geotropical distribution. For example, the western United States, Mexico, Turkey, and China’s Yunnan and Tibetan regions have the conditions for the joint development of solar and geothermal energies. In 2006, the first solar-geothermal hybrid power generation system was implemented based on the Cerro Torre geothermal power station in Mexico. The combination of solar and geothermal energies can offset the drawbacks of an independent power plant to a certain extent, not only improving the thermal performance of geothermal power plants but also reducing the cost of solar power generation. A representative design had an incremental solar efficiency of 12.2%, and its consumption was 17% lower than that of a similar stand-alone geothermal plant. Given its operational reliability and environmental acceptability, SGH systems will find a wider application in the nearest future.

4.1.3 | Mine geothermal power generation

With the development of mining of mineral resources in China, the depth of mines is gradually increased, as well as temperature and heat-induced damage. On the contrary, the geothermal resources of mines are continuously enriched. In South Africa, the mine temperature reaches 50°C at a depth of 3300 m, while the Fenghe lead-zinc mine in Japan is affected by hot water, and the temperature is as high as 80°C at a depth of 500 m. In recent years, China’s mines have gradually entered the stage of deep mining. The average mining depth reached 800 m and increases by 8-12 m per year. In some mines of the depth exceeding 1 km, the temperature of the original rock was as high as 40-45°C, and the working face temperature reached 34-36°C. Now, the main purpose of geothermal mine utilization is to use water source heat pump technology to extract the heat from the mine and eventually utilize it for heating, aquaculture, and other needs of nearby residents. In 2008, the Netherlands used abandoned geothermal resources to build a new type of geothermal power station, which proved that the use of geothermal power in mines is technically feasible. Besides, it

| Sequence | Calculation of burial depth (km) | Thermal energy (×10^25 J) | Conversion to standard coal (×10^7 million tons) |
|----------|----------------------------------|---------------------------|-----------------------------------------------|
| 1        | 3.0-4.0                          | 0.19                      | 6.5                                           |
| 2        | 4.0-5.0                          | 0.25                      | 8.4                                           |
| 3        | 5.0-6.0                          | 0.30                      | 10.3                                          |
| 4        | 6.0-7.0                          | 0.36                      | 12.2                                          |
| 5        | 7.0-8.0                          | 0.42                      | 14.1                                          |
| 6        | 8.0-9.0                          | 0.47                      | 16.1                                          |
| 7        | 9.0-10.0                         | 0.53                      | 18.0                                          |
| 3.0-10.0 km | 2.52                                | 85.6                      |                                               |

**Table 4** Assessment of the HDR resources with the depth of 3.0-10.0 km in China

| Country     | 1995 | 2000 | 2005 | 2010 | 2015 | 2016 | 2017 | 2018 |
|-------------|------|------|------|------|------|------|------|------|
| United States | 2817 | 2828 | 2893 | 3098 | 3450 | 3567 | 3591 | 3639 |
| Philippines | 1545 | 1931 | 1978 | 1904 | 1870 | 1868 | 1868 | 1868 |
| Indonesia   | 301  | 590  | 850  | 1197 | 1340 | 1375 | 1809 | 1948 |
| Turkey      | 20   | 20   | 94   | 407  | 775  | 1100 | 1347 |       |
| New Zealand | 265  | 365  | 425  | 762  | 967  | 980  | 980  | 1005 |
| Mexico      | 743  | 843  | 960  | 958  | 1005 | 926  | 951  | 951  |
| Italy       | 632  | 785  | 791  | 843  | 916  | 944  | 944  | 944  |
| Iceland     | 20   | 172  | 202  | 573  | 665  | 665  | 710  | 755  |
| Kenya       | 45   | 45   | 167  | 202  | 607  | 676  | 676  | 676  |
| Japan       | 414  | 535  | 534  | 536  | 520  | 537  | 542  | 542  |
| China       | 28   | 28   | 28   | 24   | 27.7 | 27.7 | 27.7 | 27.7 |

**Table 5** Geothermal power installed capacity changes in several countries in 1995-2018 (MW)
is possible to use abandoned mines for developing geothermal power plants, accumulating research data, and training on EGS technologies.75 Although the current use of geothermal power in mines is not cost-effective yet, with the increasing depth of mining, the geothermal temperature of mines will continue to rise, accompanied by a breakthrough in the low-temperature geothermal power generation technology. Cost-effective and rational development of mine geothermal resources will also become possible.

**4.2 The roadmap of EGS development and utilization**

China is rich in HDR resources, which can be cost-effectively developed via EGS technology. However, the latter implementation in China (even as the pilot project) is hindered by the high initial investment, long investment recovery period, high investment risks, and induced seismic

| FIGURE 8 | Distribution of geothermal power plants in China with the indication of geographic location, temperature of geothermal water, type of the power cycle, time of establishment, and scale of the plant13 |
| FIGURE 9 | (A) 400-kW screw expander power generation test unit; (B) 500-kW assembled screw expander-generator unit19 |

| TABLE 6 | Operation data of oilfield-associated geothermal power station, in the Huabei Oilfield of China48 |
| Water flow rate (m³/d) | 2880 |
| Inlet water temperature (°C) | 110 |
| Outlet water temperature (°C) | 85-90 |
| Working fluid | R123 |
| Installed power (kW) | 400 |
| Output power (kW) | 360 |
| Net power (kW) | 310 |
| Total generated energy (kWh) | $31 \times 10^4$ |
activity. In 2011-2015, many research institutes of China investigated many aspects of EGS, such as geological exploration, high-temperature deep drilling, and hydraulic fracturing. Noteworthy are results obtained by Jilin University, Tsinghua University, Guangzhou Institute of Energy Research, Tianjin University, China University of Mining and Technology, etc, which made it possible to make some progress in the key technologies related to geothermal power generation. For the period from 2016 to 2020, the “Thirteenth Five-Year Plan for Geothermal Energy Development and Utilization” was adopted in China, which stated that HDR power generation tests should be actively conducted and selected in resource-rich regions such as southern Tibet, western Sichuan, western Fujian, Fujian, North China Plain, and Changbai Mountain. Through the establishment of 2-3 HDR exploration and development of
pilot bases, the formation of technical groups and related companies, the industrial implementation of this technology is envisaged. Tibet’s Yangbajing was considered the most lucrative site for the EGS pilot project due to its abundant high-temperature geothermal resources, and existing exploration data and ancillary facilities, which would greatly reduce the construction investment and risks. Figure 15 illustrates the EGS power generation technology roadmap. This roadmap has formulated the midterm development plan for China’s EGS power generation technology from 2015 to 2030 and has defined the development directions and pre-achieved goals at each stage of China’s future EGS research and development.

5 | AN ACCOUNT OF POWER CONSUMERS’ DISTRIBUTION IN CHINA

5.1 | Geodemographic demarcation line (Hu line)

The distribution and further development of power plants in China (including geothermal ones) are strongly affected by the biased pattern of power consumers’ distribution along the so-called Hu line (also referred to as Heihe-Tengchong line), which is depicted in Figure 16. This imaginary line stretches diagonally across China from the city of Heihe in the north to the Tengchong county...
in the southwest. It divides the territory of China into two roughly equal parts with very contrasting population density values. Thus, only 6% of the population is located to the west of the line in the area amounting to 57% of the total area of China (including Taiwan), while the remaining 94% of China’s population inhabit the respective area of 43% to the east of the line.85,86 Noteworthy is that these figures changed only by 2% since 1935 when this geodemographic line was introduced by Chinese population geographer Hu Huanyong. In 1935, the respective breakdown (with the inclusion of Mongolia and exclusion of Taiwan in the map of China) was...
as follows: 64% of the area with only 4% of the population to the west of the line versus 36% of the area with 96% of the population to the east of the line. The reasons for such a trend, such as migration to urban areas, are outside the scope of this study, while its impact on the demand of power consumers in China is critical. The comparative analysis of Figures 16 and 8 shows that the dominating share of geothermal plants is located to the east of the Hu line, which complies with the power demand distribution. On the other hand, the majority of the most lucrative high-temperature domains shown in Figure 7 (in particular, at the drilling depths of 7.5-9.5 km), which are very promising for geothermal power generation, are located to the west of the Hu line. This implies higher transfer costs of the generated electricity to end users and reduces the cost efficiency of such implementations at larger distances from industrial consumers. However, given the latest postindustrial development trends, noteworthy is also the issue of discounted electricity rates and their utilization by “digital users,” including bitcoin mining farms.

### 5.2 State-of-the-art consumers of discounted electricity

Noteworthy is the fact that an increasing share of green energy production, which is supported worldwide by the national governments, is actually “converted” into digital cryptocurrency. Thus, in 2016, overcapacity from hydropower stations in Yunnan and Sichuan amounted to 45.6 terawatt hours that implied the discounted electricity rates. These attracted such exotic users as cryptocurrency miners to Sichuan, Xinjiang, and especially to Inner Mongolia, where kilometers of mining farms convert cheap electric power into bitcoins and other cryptocurrencies. Over half of the world’s bitcoin mining farms are located in China, whereas their power consumption worldwide accounts for 0.5% of the world’s annual electricity production and keeps growing. Since electricity sharing between energy companies and miners in China still falls into a “gray zone,” where the discounts can be exchanged for mining revenue cuts, quite expedient are recent measures of the China
government in 2017 to shut several mines in Sichuan, due to lack of respective regulations. Given this, instead of using surplus power from hydropower stations, big mining companies seek for discounted supply from the State Grid, which is the state-owned electricity utility.89 In this respect, noteworthy is the link between geothermal power generation and demand of cryptocurrency mining consumers. In Iceland, where most electricity is produced by geothermal and hydroelectric plants, its consumption by cryptocurrency mining in 2017 exceeded that of all households: 840 versus 700 gigawatt hours of electricity, respectively. It doubled the national energy consumption in 2017 and experienced exponential growth in 2018, which may overburden the respective equipment.90 A similar boom is observed in China, which may be followed by a drastic drop since some experts claim that “all mines will get dry someday” and cryptocurrency miners may become a problem for their energy-generating partners. The respective regulations and strategies have to be included in the comprehensive analysis of the geothermal power generation prospects in China.

6 | PROSPECTS OF GEOTHERMAL POWER GENERATION IN CHINA

Geothermal energy should be seamlessly incorporated into the national energy and climate improvement plans. The direct utilization of low-temperature geothermal resources in China has been well developed, but the application of geothermal power generation is still at an early stage. Compared with other green (wind, solar, etc) energy power generation methods, geothermal power has the advantages of abundant reserves, low cost, and durable stability. However, the development of geothermal energy is much slower than that of wind and solar renewable energies. The development of new energy depends in no small extent on the government’s policies, regulations, incentives, and initiatives. Therefore, there should be clear guidelines for incorporating the geothermal energy into the national energy top-level strategic plan. Governments can promote the development of geothermal power generation in the following aspects: (a) formulate the geothermal power generation support and on-grid tariff policies; (b) improve the geothermal energy development and utilization market mechanism; (c) strengthen the geothermal energy development and utilization planning and project management; (d) improve geothermal power generation management systems and technical standards; and (e) increase investments into R&D of key equipment and technologies. Comprehensive utilization of HDR in China has the top priority. In the past two decades, the development of geothermal power generation in China has stagnated, but the United States, Japan, and other countries have carried out a large number of exploration, experimental research, and especially accumulated rich experience in HDR-related technologies.
Therefore, China should promote international cooperation, implement advanced foreign technologies, and adapt them to domestic geothermal geological conditions to form a model suitable for the comprehensive utilization of HDR in China. In the future, HDR resource exploration and EGS R&D works should be carried out, focusing on the following areas: (a) HDR resource evaluation and EGS site selection; (b) deep and high-temperature drilling technology R&D; (c) geothermal reservoir creation technologies (hydraulic fracturing, chemical stimulation, blasting-fracturing, etc); (d) geophysical prospecting techniques; and (e) microseismic, tracing, and other monitoring techniques. The purpose is to evaluate the reservoir lamination splitting effect and tracking the fluid flow.

The development and utilization of geothermal resources should adhere to the principle of adaptation to local conditions and rational approach. According to the reserves and distribution characteristics of geothermal resources in China, geothermal generation should be mainly developed in areas rich in high-temperature geothermal resources such as southern Tibet, western Sichuan, western Yunnan, and Taiwan. For the medium- to low-temperature geothermal resources regions, geothermal heating will be developed in the northeast and north China, geothermal cooling will be developed in the southeast coastal areas, and medium- to low-temperature geothermal power generation should be given priority under appropriate conditions. Tibet's Yangbajing is considered the most lucrative site for the EGS pilot project due to its abundant high-temperature geothermal resources. Moreover, Tengchong in Yunnan Province, Zhangzhou and Fuzhou in Fujian Province, and Yangjiang in Guangdong Province are potential target areas for China EGS demonstration projects.

In some areas with abundant geothermal resources, the level of their development and protection is quite low yet. To improve the utilization ratio of geothermal energy and reduce the waste of resources, a cascade utilization model of geothermal resources should be formed, to provide the cost-effective and efficient utilization of geothermal resources. The concept of cascade utilization can be described as the harnessing of geothermal heat at different thermal levels in sequential processes. As can be seen in Figure 17, the cascade utilization geothermal system can be designed as a multiple-level cascade for different purposes, such as power generation and thermal uses.

7 | CONCLUSIONS

This study provides a state-of-the-art outlook on the distribution and amount of geothermal resources and the status of geothermal power generation in China. China has abundant geothermal resources including shallow geothermal resources, hydrothermal geothermal resources, and HDR resources. The direct utilization of geothermal resources has been well developed, while the geothermal power generation is yet underdeveloped. The total installed capacity of geothermal power generation in China at this stage is 27.78 MW (Tibet Yangbajing [26.18 MW], Yangyi [0.9 MW], Guangdong Dengwu [0.3 MW], and Huabei Oilfield [0.4 MW]), which is far from United States (3639 MW) and Indonesia (1948 MW). Insofar as the geothermal resources in China are unevenly distributed, the development and utilization of geothermal resources should adhere to the principle of adaptation to local conditions and rational approach. It is should mainly develop geothermal power generation in the areas rich in high-temperature geothermal resources such as southern Tibet, western Sichuan, western Yunnan, and Taiwan. For the medium- to low-temperature geothermal resource regions, the medium- to low-temperature geothermal power generation should be given priority under appropriate conditions, while the direct utilization is optional. The solar-geothermal hybrid power generation can not only improve the thermal performance of geothermal power plants but also reduce the cost of solar power generation. Moreover, the
oil-geothermal and mining geothermal power generations also have excellent development potential.

The reserve of HDR resources in China is equivalent to \(85.6 \times 10^5\) billion tons of standard coal, which is 3927 times higher than China's current total energy consumption. However, the development and exploration of HDR resources in China are far below expectations due to the immaturity of EGS technology. It is urgently needed to establish 2-3 EGS pilot projects to accumulate the required experience and achieve technological breakthroughs. Tibet's Yangbajing is considered the most lucrative site for EGS pilot project due to its abundant high-temperature geothermal resources. Moreover, Tengchong in Yunnan Province, Zhangzhou and Fuzhou in Fujian Province, and Yangjiang in Guangdong Province are potential target areas for China's EGS demonstration projects.

The distribution and further development of power plants in China (including geothermal ones) are strongly affected by the biased pattern of power consumers' distribution along the so-called Hu line. The concentration of 96% of China's population in the area to the east of Hu line affects the perspectives of high-cost geothermal projects and has to be accounted for in the comprehensive analysis of available data.

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CONFLICTS OF INTEREST
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