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RESEARCH ARTICLE

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Strategic analysis of China's geothermal energy industry

Abstract China is an early user of geothermal energy, and its direct use ranks first in the world. Recent national strategies and policies have enabled China's geothermal energy industry to enter a new era with important development opportunities. This paper investigates the strengths, weaknesses, opportunities, and threats (SWOT) to China's geothermal energy industry from political, economic, social, and technological (PEST) perspectives. SWOT–PEST analysis indicates that the resources, market, and technological foundation exist for the large-scale development of China's geothermal energy industry. However, it experiences constraints, such as unclear resource distributions, incomplete development of government regulations, incomplete implementation of national policies, unclear authority between governmental administrative systems, and lack of uniform technical standards and codes. Therefore, future development strategies have been proposed to provide technical support and policy tools for geothermal energy development. The recommendations to ensure its healthy and sustainable development include improving resource exploration, rationalizing administration systems, enhancing policy guidance and financial support, and cultivating geothermal talent.

Keywords geothermal energy, strategic analysis, SWOT–PEST, policy, administration

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1 Introduction

A booming energy revolution has set major countries in the world toward developing non-fossil energy sources to reduce greenhouse gas emissions and to promote energy transformation (Geller, 2012; Zou et al., 2016; Kumar et al., 2019; Lian et al., 2019). After more than 30 years of rapid economic growth, China's energy resource constraints have intensified, ecological and environmental problems have become increasingly acute, and per capita resources and environmental capacity are remarkably lower than global average values. China's energy development faces new problems and challenges and the pressure to ensure energy security and improve energy efficiency. Under a goal of "promoting the revolution of energy production and consumption", vigorous development of non-fossil energy has become the consensus in China (Mathews and Tan, 2015; Liu et al., 2018).

Geothermal energy is a realistic and competitive renewable energy source that is environmentally friendly, widely used, stable, and recyclable (Massachusetts Institute of Technology-led Interdisciplinary Panel, 2006; Guan et al., 2018; Cui et al., 2019). China is an early adopter of geothermal energy (Huang, 2012; Xiong et al., 2015). China's geothermal energy utilization is mainly for direct heating or cooling (Hou et al., 2018), with utilization reaching 48435 GWh in 2014 and annual utilization rate ranking first in the world for many years. At the end of the

12th Five-Year Plan in 2015, China's national geothermal heating/cooling area is approximately 500 million m^2. However, the installed power generation capacity nationwide is 27.28 MW, only accounting for approximately 0.2% of the global total operating capacity (Geothermal Energy Association, 2016). This finding indicates that direct heating and cooling are better developed than power generation.

Figures 1 and 2 show the scale of shallow geothermal heating/cooling and hydrogeothermal heating in different provinces and cities (Hu, 2017). Hot dry rock (HDR) resources are still in their exploratory stage and have not been utilized in China (Wan et al., 2005; Feng et al., 2012). Table 1 shows the exploration and development status of HDR resources, which is mainly concentrated in Gonghe, Qinghai.

In 2015, the annual utilization of China's geothermal energy is equivalent to approximately 20 million tons of coal, accounting for 0.47% of 2015 annual primary energy consumption. China's geothermal utilization structure is similar with the global status. In particular, China's direct heating and cooling utilization is growing faster than geothermal power generation.

The 13th Five-Year Plan for Energy Development

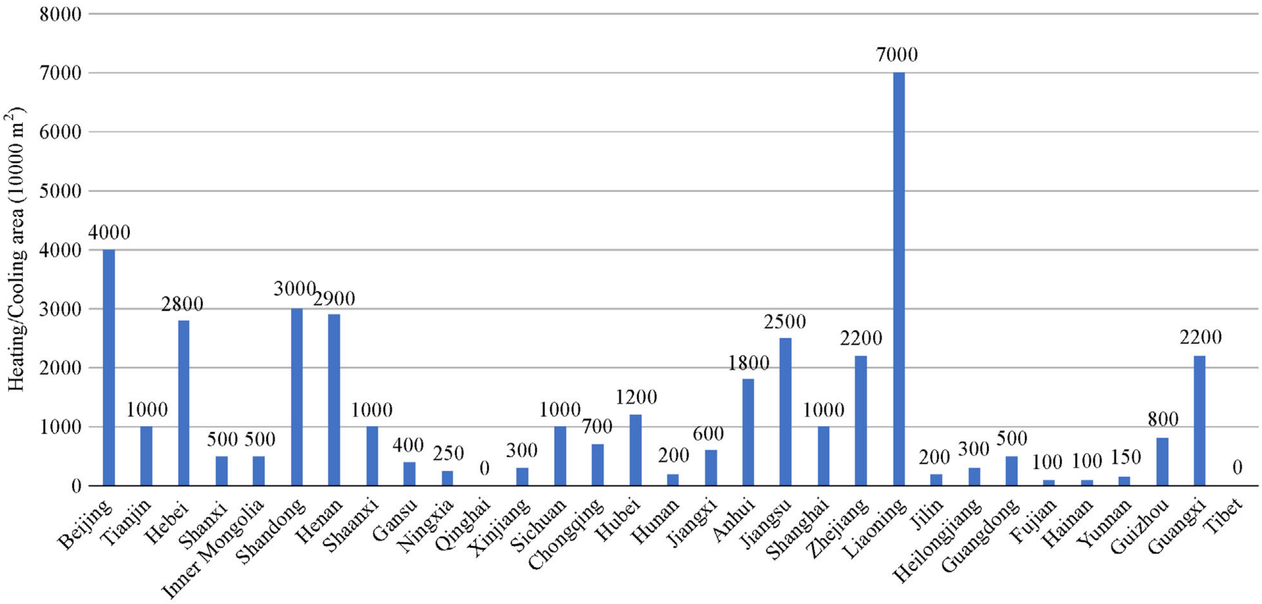

Fig. 1 Shallow geothermal heating (cooling) scale of different provinces and cities of China (at the end of 2015).

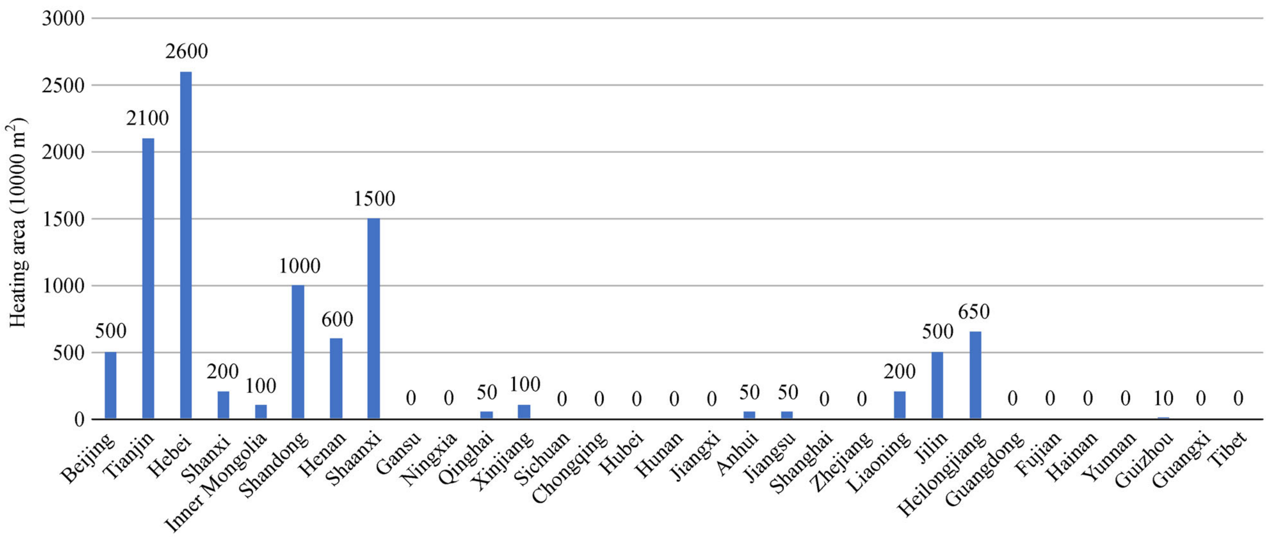

Fig. 2 Hydrogeothermal heating scale of different provinces and cities of China (at the end of 2015).

Table 1 China's HDR exploration and development

Geothermal region	Well No.	Well depth (m)	Bottom temperature (°C)	Utilization status
Qiabuqia, Gonghe Basin	DR3	2927	183	Heating for hospital
	DR4	3102	181	Tentative power station
	DR4	3102	181	Tentative power station
	GR1	3703	236	Pumping test
	GR2	3000	182	Sealing
Zhacanggou, Guide Basin	ZR1	3051	151	Sealing and monitoring
	ZR2	4300	175	Under construction
Qiongbei, Hainan	Huadong No. 1	4387	185	Tentative research

objective is for the use of non-fossil primary energy consumption to increase from 12% in 2015 to 15% by 2020. Geothermal energy is expected to account for approximately 1% in the 3% increase in non-fossil energy. However, China's renewable geothermal energy sector is still emerging. Despite a long history of development and utilization, the geothermal sector has been in a tepid state for decades. Common problems in renewable energy and special problems within geothermal energy have been revealed during their development in China. These problems include unclear resource distributions, incomplete development of government regulations, incomplete implementation of national policies, unclear authority between governmental administrative systems, and lack of uniform technical codes and standards. In particular, the current top-level design and planning cannot guarantee the large-scale development of geothermal energy.

This paper conducts an analysis of the current strength, weakness, opportunities, and threats (SWOT) from political, economic, social, and technological (PEST) perspectives to improve the efficiency of China's geothermal energy utilization and promote its healthy development in the new era characterized by consumption-led growth and innovation. Strategic planning suggestions on the basis of this SWOT–PEST analysis are proposed as scientific reference for the rational development, utilization, and protection of geothermal energy resources.

The rest of this paper is organized as follows. Section 2 explains the data collection and SWOT–PEST analysis. Section 3 analyzes the opportunities, challenges, and features of the geothermal industry in recent years. Section 4 conducts an analysis of China's geothermal industry development strategy to develop suggestions for improvement. Section 5 summarizes the work.

2 Analysis method and data collection

2.1 Methods

SWOT analysis is used to comprehensively evaluate, analyze, and obtain relevant conclusions from the strengths, weaknesses, opportunities, and threats of an organization or region (Pickton and Wright, 1998). SWOT analysis is useful for the timely adjustment of strategies, integration of internal/external resources with the environment, and promotion of internal development. PEST analysis is a management method where an organization can assess the influences of its macro-environment on its operations to become competitive in the market (Gupta, 2013). SWOT and PEST analyses are not limited to planning and development of individual organizations and are widely applied to market analysis and tactical research and evaluation of development prospects with focus on solving real problems.

In recent years, an integrated SWOT–PEST analysis applicable to many industries and fields has emerged, with a structured approach and reasonable clustering characteristics (Ha and Coghill, 2008). In this work, each internal strength and weakness of the geothermal energy sector are compared and evaluated for their political, economic, social, and technological dimensions through SWOT–PEST analysis. The external opportunities and threats in the geothermal energy sector are evaluated in terms of their PEST dimensions.

2.2 Data collection

An accurate, objective, and in-depth understanding of China's geothermal industrial status was required by conducting several surveys as follows:

- Investigate "Transfer from coal to geothermal heating" project at Beijing–Tianjin–Hebei region, Henan, Shandong, and other places for their actual operation;
- Investigate the current status of shallow geothermal energy development and utilization at Shanghai, Jiangsu, Chongqing, Zhejiang, Hubei, and Hunan;
- Investigate the development status of geothermal power generation at Sichuan and other places;
- Investigate the status of HDR exploration and development at Qinghai, Hainan, and other places;
- Survey on market prospects, economic benefits, and

technology maturity at Sinopec Xinxing, Henan Wanjiang, Sichuan Kangsheng, Nanjing Fengsheng, Zhejiang Lute, and other companies.

Seminars were conducted to obtain extensive input from industry experts on the existing problems in China's geothermal industry and their opinions on follow-up development. The systematic SWOT–PEST analysis result of the data are outlined in the following sections.

3 SWOT–PEST analysis of geothermal energy development in China

This section evaluates the strengths (S), weaknesses (W), opportunities (O), and threats (T) in China's geothermal energy development and utilization and discusses these factors from political (P), environmental (E), social (S), and technological (T) perspectives. For reference, each evaluative dimension will be labeled with its perspective, e.g., an environmental strength is labeled with SE.

3.1 Strengths

The relative strengths of China's geothermal industry include supporting policies and regulations at the national and local levels (SP), stable and sustainable geothermal project revenues (SE), huge resource potential (SS-1), obvious environmental benefits (SS-2), and accumulated successful experience in geothermal heating (ST).

3.1.1 Policies and regulations at the government level (SP)

Environmental laws and regulations, including the Renewable Energy Law promulgated after 2000, partially covered the development and utilization of geothermal resources. In addition to regulations, the government has issued administrative documents covering fiscal and taxation, subsidies, and other industrial supporting policies in the past decade (Luo, 2017; Hou et al., 2018).

Several local governments have issued policies, including management methods, regulations, and engineering implementation plans for geothermal resources/energy to promote the utilization of local geothermal resources. Examples of these local policies include Administration Measures of Geothermal Resources in Beijing, Administration Measures of Geothermal Resources in Tianjin, Management Regulations of Geothermal Resources in Yunnan, and Management Regulations of Geothermal Resources in Inner Mongolia.

Although geothermal projects, especially geothermal heating projects, can support people's livelihoods, they have high initial investment requirements. Therefore, corresponding supporting policies are extremely important for geothermal energy utilization. For instance, several local governments have released fiscal and tax subsidy policies. In fact, different regions have reasonably adopted local supporting policies on the basis of local resource advantages and environmental constraints. In addition to ensuring sustainable utilization of local geothermal resources, these policies can alleviate pressures for controlling air pollution, conserving energy, and reducing emissions.

3.1.2 Sustainable revenues of geothermal projects (SE)

Unlike oil and natural gas, the price of geothermal projects is less volatile because of market fluctuations. A geothermal project can have a long-term operational lifespan of 30–50 years.

The return on investment rate of traditional energy projects is higher at first and then reduces over time by comparing an oilfield and a geothermal heating project. However, the life cycle return on investment rate for geothermal heating projects shows a high–medium–high trend, as shown in Fig. 3. The annual project construction costs are classified as income sharing, low in the middle,

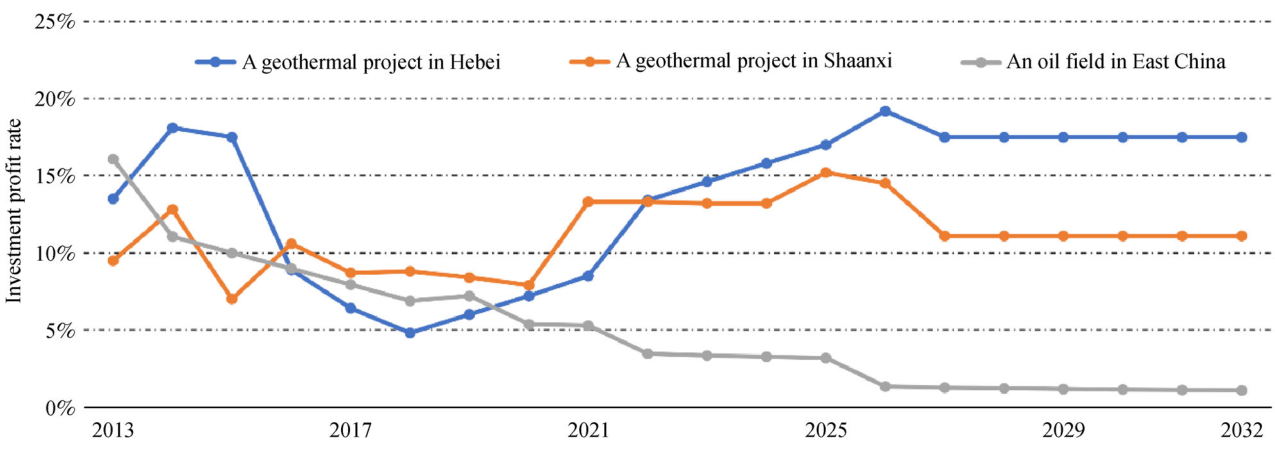

Fig. 3 Comparison of life cycle profit rate trend between geothermal and oilfield projects.

and high in later period. After considering the depreciation, the economic benefits continue at a good level because of low operational costs.

3.1.3 Huge resource potential (SS-1)

China's geothermal resources are abundant, with approximately 2.6 billion tons of standard coal per year. These resources can be extracted from hydrothermal and shallow geothermal energy resources, and actual annual drilling volume only accounts to 20 million tons of coal per year at the end of the 12th Five-Year Plan (Hu, 2017). Therefore, China's geothermal resources have an extremely good utilization potential.

In addition, HDR geothermal resources are strategic alternative energy sources. The China Geological Survey indicates that HDR resources at the depth of 3.0–10.0 km are approximately 25.2×10^6 EJ, which is equivalent to 856 trillion tons of standard coal. More than 3800 times China's energy consumption in 2017 could be covered when only 2% of the resources is harnessed (Wang et al., 2017).

3.1.4 Significant environmental benefits (SS-2)

The Boiler Air Pollution Emission Standard (GB13271-2014) limits of sulfur dioxide, nitrogen oxides, and soot emissions for coal-fired heating boilers are 400, 400, and 80 mg/m^3, respectively. The Full Implementation of the Ultralow Emission and Energy-saving Renovation Work Plan for Coal-fired Power Plants issued in 2015 limits sulfur dioxide, nitrogen oxides, and soot emissions for coal-fired power plants to 35, 50, and 10 mg/m^3 by 2020, respectively. Heating boiler emissions are approximately 10 times higher than that of plant boilers. The emissions of scattered coal combustion plants are dozens of times higher than the emissions of coal-fired power plants.

Solar and wind power generation can reduce the pollutants emitted by coal-fired power plants, and geothermal heating can reduce the pollutants from coal heating boilers and direct coal burning for rural heating. Therefore, the development of geothermal heating for atmospheric pollution prevention will be significantly prominent in China in the coming years.

3.1.5 Successful experience on geothermal heating (ST)

In Hebei Province, Xiong County (now part of Xiong'an New Area) has reached 5.7 million m^2 of geothermal heating capacity after approximately 10 years of construction. Xiong County has essentially achieved full coverage of geothermal central heating, becoming China's first "smoke-free city" (Hu and Zhang, 2017). This large-scale geothermal central heating project is the largest in the world. In addition, Xiong County has realized energy-saving, large-scale development, and utilization of "heat extraction without water consumption". Xiong County has extended its geothermal heating system into neighboring rural areas, completely replacing coal for heating in those areas (Hu and Zhang, 2017). This development model has immensely enhanced the public understanding of geothermal energy resources and indicated the China's growing geothermal sector.

3.2 Weaknesses

The relative weaknesses of China's geothermal industry include unclear geothermal resources (WP), rough financing channels (WE), insufficient talent reserves (WS), and underdeveloped technologies (WT).

3.2.1 Unclear overall geothermal resources (WP)

On the basis of the National Geological Exploration Results, 577.3 billion yuan were invested in national geological exploration during the 12th Five-Year Plan, in which only 416 million yuan were invested in geothermal resource exploration, accounting for less than 0.12% of investment in oil, gas, and mining exploration, as shown in Fig. 4. The details about national geothermal resources are urgently needed.

The total amount of available geothermal resources in China is a rough estimate because of the significant gap between the level of China's geothermal resource database and that of developed countries. Although China and the United States have a similar land area, the United States obtains data on more than 17000 geothermal sites, while the current published heat flow sites in mainland China are only 1230 (Jiang et al., 2016). In some areas, geothermal resource amount is undervalued, and exploratory evaluation lags behind the development and utilization needs.

A unified national geothermal resource information system is lacking, being short of the necessary information for its management. A geothermal resource information database has not been established in China, making it difficult to provide basic information for the exploration and orderly development of geothermal resources.

3.2.2 Lack of funds, poor financing sources, and limited scale of development (WE)

Several alternative projects of coal-fired power have been surveyed to compare the economic issues between geothermal and other heating methods, as shown in Table 2. This survey indicates that geothermal projects have low operating costs and economic burden to users. However, the initial investment from enterprises is

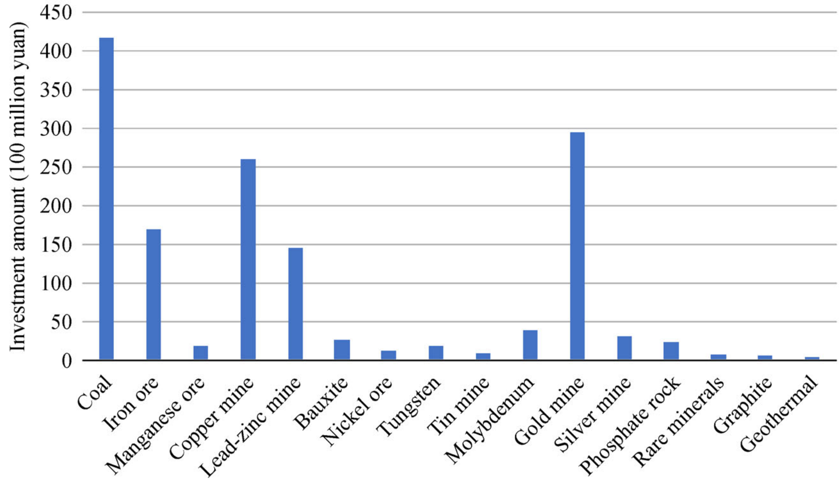

Fig. 4 Comparison of China's investment on key minerals and geothermal exploration during the 12th Five-Year Plan period.

Table 2 Economic analysis of bulk coal substitution projects (surveyed in the rural area in Hebei)

Projects	Initial investment (yuan per 100 m^2)			Heating costs (yuan per 100 m^2 per heating season)		
	Enterprise	Government	Farmer	First three years		After three years
				Government	Farmer	Farmer
Coal to electric	3300	7400	1305	2000	1056	3056
Coal to gas	7000	6700	1450	1200	1800	3000
Coal to geothermal energy	9600	7400	0	2000	1600	1600

relatively high, and the investment recovery period is long.

Although a geothermal project can save considerable fuel costs when its operation starts, factors, such as high initial investment, high exploration risk, and long payback periods, make geothermal projects relatively difficult to initiate, resulting in insufficient investment from social capital. The geothermal industry is currently in its early stages, and the scale of geothermal enterprises is small. Most of these enterprises do not have the ability to finance by issuing stock in open capital markets. These financing difficulties and problems are common.

3.2.3 Low overall levels of talents (WS)

China has lacked in geothermal talent resources and original research is relatively weak, for a long time period. National colleges and universities have not offered a major in geothermal energy. Only a few dozen graduate students are found in the geothermal area each year. With an increasing demand from the geothermal market, the supply of talent resources would be short (Huang, 2014).

3.2.4 Underdeveloped critical technologies (WT)

Technical challenges for exploiting geothermal energy resources include the low recharge rate of hydrogeothermal heating, which affects the revenue after thermal extraction and sustainable utilization of resources. This challenge may also cause other problems, including drop in groundwater level and surface water pollution. The level of system design, construction, and operation of shallow geothermal utilization needs improvement.

Although China's geothermal technology is mature, several key technologies for sandstone economic recharging and commercial development of HDR remain to be grasped. Gaps are found in the advancement of technology levels and equipment globally, including medium- and low-temperature high-efficiency power generation, heat pump core components, high-efficiency heat transfer, and anticorrosion (Hou et al., 2018). Thus, some geothermal resources are inefficiently utilized, without obvious economic benefit, and may cause environmental pollution, thereby limiting the orderly development of the geothermal industry.

3.3 Opportunities

Opportunities for geothermal energy mainly include the release of national strategy and plan (OP), growing market (OE), positive social attention (OS), and progress in new technologies (OT).

3.3.1 National strategy and plan for geothermal energy (OP)

In July 2016, the China State Council issued the 13th Five-Year National Science and Technology Innovation Plan. One mission of this plan is an Earth's Deep Exploration Major Science and Technology Project, conducting research on geothermal exploration and its efficient utilization. In December 2016, the national government has emphasized the promotion of clean heating in Northern regions during winter, where traditional high-consumption, high-pollution heating methods will be gradually replaced by clean, low-carbon heating methods. The key areas for this strategy are highly coincidental with the concentrated distribution of geothermal resources, because medium and deep geothermal resources in six Northern provinces and cities (identified by the Ministry of Environmental Protection as air pollution transmission channel cities) have the potential to replace 867 million tons of standard coal per year. Shallow geothermal energy resources can replace additional 176 million tons of standard coal annually. This resource potential is sufficient to support clean heating in Northern China, and geothermal heating can be the main method for clean heating (Zhou et al., 2015).

In January 2017, the National Development and Reform Commission with other ministries jointly issued 13th Five-Year Plan of China's Geothermal Energy (Hu, 2017). This national plan immensely promotes the rapid large-scale development of China's geothermal industry. In April 2017, Xiong'an New Area was established by the Chinese government (Hu and Zhang, 2017; Xiao and Zhao, 2017). A recent geological survey shows that Xiong'an New Area has abundant geothermal resources with the best utilization conditions in Central and Eastern China. The heating and cooling demands of Xiong'an New Area can be met in the future, thereby immensely promoting the high-end development of China's geothermal industry.

3.3.2 Growing market for geothermal energy (OE)

The proportion of China's urbanized population has increased from 38% in 2001 to more than 55% in 2015 (Guan et al., 2018). Rapid urbanization has led to a significant increase in construction and its consequent heating needs. By the end of 2016, the total area of heated buildings in Northern China reached 20.6 billion m^2, representing an annual growth rate of approximately 10%. Heating needs will continue to grow in the future. At the same time, improved living standards have increased the demand for heating in Southern China.

Shallow geothermal energy resources in Southern China are abundant. In particular, surface water, including rivers and lakes, is abundant and is suitable for heat pump systems for heating and cooling. Therefore, the shallow geothermal energy market in Southern China may significantly increase in the future. Other industries, such as specialized agricultural and aquatic products, and agricultural tourism, have increased the demand for heated greenhouses in recent years, which provides a good opportunity for geothermal resource utilization in agriculture.

3.3.3 Positive social attention to geothermal energy (OS)

Currently, global attention is focused on clean heating/cooling resources, such as REN21 (Renewable Energy Policy Network for the 21st Century)'s Renewables 2018 Global Status Report. This report indicated that the renewable energy transformation in heating and cooling of the transportation sectors lag behind that of the power industry. In the future, heating and cooling sectors can accelerate change by aligning their transformation model to that of the power industry model. In advancing a clean winter heating in the Northern region agenda, China has focused attention on the geothermal heating industry. Overall, the geothermal industry is experiencing positive outside attention to its development activities.

3.3.4 Progress in emerging technologies (OT)

Many geothermal enterprises, such as Sinopec, Zhejiang Lute, and Nanjing Fengsheng, have developed information technology applications for the geothermal industry. Sinopec developed a 3D geothermal resource development and control system, which is China's first domestic geothermal regulation and control platform. This system optimizes the heat supply to reduce the operating costs. The integration of information technology into geothermal energy can improve energy efficiency and enhance economic benefits. The operational control system can access weather forecast data and automatically adjust the amount of thermal extraction in accordance with real-time temperature analysis.

For dynamic monitoring of geothermal wells, sensors can be installed in and on the ground to monitor parameters, such as heat storage pressure, temperature, fluid chemical field, geothermal field, and geophysical field. A thermal storage engineering model can form the basis for dynamic monitoring. The storage model can guide thermal extraction and management to achieve efficient and sustainable development and utilization of geothermal energy. In the future, the geothermal industry has the potential to be upgraded with technologies, including integrated design, modular construction, digital sensing, green engineering technologies, intelligent manufacturing, and human–cyber–physical systems (Zhou et al., 2018; 2019; Liu et al., 2019).

3.4 Threats

Threats to China's geothermal industry include shared regulatory authority (TP), industrial policy (TE), inconsistent regulatory approach (TS), and parallel energy technologies (TT).

3.4.1 Shared regulatory authority (TP)

Geothermal energy has been classified as an "energy mineral extraction" activity that is clarified in laws, such as the Renewable Energy and Mineral Resources Laws (Wang, 1998; Li, 2005). Unlike hydrocarbon deposits (coal, oil, and natural gas), underground water is an important carrier for geothermal energy utilization. Therefore, the utilization of geothermal energy is subject to the Water Law. Land, water conservation, and energy ministries are all involved in the management of geothermal energy. At present, the division of geothermal regulation management at the national level remains unclear. In local areas, few regions have issued guidance to clarify the division of management or introduced regulations for its management. An unclear division of responsibility for geothermal management requiring multi-level approvals is inefficient, making the harmonization of national, provincial, city, and county level interests important. Offside, vacancy, mutual restraint, and repeated law enforcement frequently occur (Gong et al., 2018). Therefore, normative geothermal energy management is difficult to guarantee.

3.4.2 Industrial policy (TE)

The implementation of geothermal energy in industries is difficult because more than 10 plans about the utilization of geothermal energy spread over several ministries, causing problems for its systematic coordination. These plans have conflicts in their preparation, implementation, evaluation, and feedback. A lack of comprehensive coordination has limited the efficiency of those plans because the responsibility overlaps in several departments.

The financial support for geothermal energy is insufficient. Although the 13th Five-Year Plan for Geothermal Energy has been released, China has not issued a corresponding financial support policy. At present, few regions have released subsidy policies for shallow geothermal energy industries with a high degree of marketization, mainly focusing on policies for encouragement and guidance. No supporting policies are available for hydrogeothermal heating and geothermal power generation.

The tax policy for geothermal energy is not well targeted. At present, the geothermal industry tax policy does not adequately account for the particularity of geothermal utilization and is lacking in pertinence. Unclear responsibility for geothermal management in land and water conservation departments compounds this haphazard tax policy. The charging standard for mineral and water resource compensatory fees have been consistently the focus of discussion in the geothermal industry.

Pricing policies for geothermal energy is incomplete. A survey of residential geothermal heating indicates that most projects are still implemented with industrial electricity price, which does not match the pricing policy given in the Guidance on Promoting the Development and Utilization of Geothermal Energy issued in 2013 (Duan, 2013). The government has not released regulations for on-grid pricing of geothermal power generation, thereby hindering the enthusiasm of energy companies to invest in geothermal power generation.

3.4.3 Inconsistent regulatory approach (TS)

Geothermal energy is defined as a mineral resource in the Mineral Resources Law, whereas it is defined as a renewable energy source in the Renewable Energy Law. This condition reflects the unique attribute of geothermal energy as the only renewable resource among all mineral resources and the only one managed as a mineral resource among all renewable energy sources. However, a key issue for China's management regulations for mineral resources is that mineral resources are limited and nonrenewable. This premise and the formulation of relevant policies are unsuitable for geothermal energy.

Currently, "heat extraction without water consumption" is the guiding principle for the utilization of hydrogeothermal energy, requiring not to consume groundwater resources or pollute surface or ground water. Geothermal energy is renewable when water is recirculated. However, a lack of understanding that geothermal energy is renewable has allowed it to be regarded as a nonrenewable mineral resource, which hinders the full-scale development of the geothermal industry.

3.4.4 Alternative energy technologies (TT)

Alternative energy technologies, including methane ice (or combustible ice) (Liao and Xiong, 2008) and clean coal utilization (Chang et al., 2016), are competing with geothermal energy. China has established a national key laboratory for combustible ice technology that is making rapid progress. A major breakthrough on combustible ice technology in the near future will immensely alleviate China's energy consumption problems and the country's demand for HDR technology may be reduced. At present, China's thermal power generation has achieved ultralow emissions, and pollutant emission standards are still improving. At the same time, the advancement of coal clean utilization technologies has immensely reduced the emissions of coal-fired boilers. Breakthroughs in carbon capture, utilization, and storage technologies will reduce the pressure for greenhouse gas emission reduction. Therefore, the relative advantages of geothermal energy in emission reduction may disappear.

4 Development strategies for China's geothermal energy industry

The SWOT–PEST analysis of China's geothermal energy industry identifies the following factors, as summarized in Table 3. An analysis of these factors was conducted to provide guidance to development strategies and policy recommendations that will maximize the advantages, fill the shortcomings, firmly grasp external opportunities, and actively respond to external challenges. These proposed recommendations are discussed in this section.

4.1 SO strategy

The following strategic plan is proposed from the perspective of chronological planning:

• Before 2035, heating should be the main application field of geothermal energy.

• The opportunity of Clean Heating in Northern China and Xiong'an New Area plans should be grasped as a breakthrough for geothermal heating for its development in rationalizing the management system, increasing policy support, helping smog treatment, and enhancing public understanding on geothermal energy.

• We should focus on key technologies in geothermal power generation and HDR exploration and strengthen the exploration and evaluation of geothermal resources. These actions will provide a solid basis for the large-scale development of geothermal power generation in the future.

• After 2035, geothermal heating and power generation are expected to go hand in hand, following the breakthroughs in HDR-related technologies.

Considering the different resources and markets in different regions of China, the following suggestions are proposed:

• Central and Eastern China can focus on the development of geothermal heating to promote clean heating plan. The demand for smog treatment in these areas is in good agreement with their geothermal resource advantage. The Beijing–Tianjin–Hebei region, Henan, Shandong, Shaanxi, and Shanxi should focus on the development of geothermal heating to replace coal-fired boilers and rural loose-coal heating.

• On the basis of China's geothermal heat flow map, abundant high-temperature geothermal resources are present in Western China, including southern Tibet, western Sichuan, and western Yunnan, although low-temperature geothermal resources are dominant all over China (Jiang et al., 2019). The potential for high-temperature geothermal power generation in this region is estimated to reach approximately 3510 MW (Duo et al., 2017). In the future, medium-high temperature geothermal power generation and HDR exploration demonstration projects should be promptly established in Qinghai, Tibet, western Sichuan, and western Yunnan to ensure clean energy supply for Western China.

• In regions with hot summers and cold winters, shallow geothermal resources are abundant, especially surface water systems, such as rivers and lakes. Hot and cold dual supply systems with high energy utilization efficiency can be provided in those regions. In the future, promoting shallow geothermal heating and cooling projects in regions including Yangtze River Delta region, Wuhan City Circle, Changsha–Zhuzhou–Xiangtan region, Sichuan, and Chongqing, is suggested.

4.2 WO strategy

The boundaries of geothermal utilization are expanding and should utilize multisource supplies of thermal energy. Urban sewage, oil production sewage, industrial wastewater, and mine return air all contain rich sources of heat. Utilizing heat pumps on these sources can provide clean, renewable electricity, and also heat to surrounding areas. With the continuous advancement in energy conservation and emission reduction, various unconventional heat

Table 3 Factors affecting geothermal energy industry development

Factors		P	E	S	T
Internal	S	Various policies and regulations introduced at the national and local levels	Rich and stable resources; stable and sustainable income	Relatively clean and safe	Successful experience in geothermal heating
	W	Unclear resource amount	High initial investment; lack of funds; poor financing channels	Rough utilization; lack of talents	Key technologies; information level; innovative ability
External	O	Ecological civilization construction; clean heating in Northern China; the Belt and Road Initiative	Expanding energy market	Characteristic agriculture; ecological agriculture	Energy Internet; big data; information technology; intelligent manufacturing
	T	Rationalizing administration systems	Inadequate industrial system	Lack of social understanding	Other renewable energy technologies

sources can be an important part of geothermal energy utilization and should be significantly supported and accelerated.

At present, the overall level of China’s geothermal industry is relatively low. Important opportunities should be grasped, and multiple measures should be simultaneously taken to accelerate the rate in which the industry upgrades. The following measures are suggested:

• Demonstration projects can lead to industry upgrades. A series of geothermal demonstration projects will contribute useful industry experience and drive the rapid development of geothermal industry in corresponding regions. Geothermal utilization in Xiong’an New Area is expected to promote the overall development of the geothermal industry in Beijing–Tianjin–Hebei region. The water-source heat pump projects in Chongqing and Nanjing can provide a good prototype for shallow geothermal utilization in regions with hot summers and cold winters.

• The industrial supply chain should be extended in multiple directions. A vertical extension should be undertaken by vigorously promoting the intensive utilization of geothermal resources. A horizontal extension should be undertaken by advocating Geothermal Plus, integrating multiple energy sources in demonstration projects, and coordinating energy supply with other renewable resources.

The research investment in key equipment and technologies should be increased as follows:

• Strengthen the research and development (R&D) investment to form the technological system of geothermal energy development and utilization, exploration and evaluation, drilling and well formation, reservoir transformation, efficient heat transfer, sandstone thermal storage and economic recharge, and medium- and low-temperature geothermal power generation.

• Improve the manufacturing capabilities of key equipment, such as heat pumps and heat exchangers (Wang et al., 2015), to accelerate the development of support technologies, including energy storage and energy-saving technologies.

• Conduct research on key scientific issues in the utilization of HDR resources.

4.3 ST strategy

The intensity of resource exploration and evaluation should be increased because they are the basis for the development of geothermal industry. A complete technical support system for investigation, evaluation, and scientific utilization of geothermal resources should be formed by:

• Increasing the investment in exploration and evaluation;

• Focusing on HDR resources;

• Creating a database of geothermal resource exploration and development, improving the assessment of geothermal reserves.

The industrial policy system should be optimized as follows:

• Strengthen the guidance on geothermal energy planning and include geothermal energy in all urban planning. The major national authorities should take the lead in formulating a national geothermal industry plan and providing guidance for the scientific and orderly utilization of geothermal energy throughout the nation. Local bureaus should set up geothermal energy development goals and include them in regional or urban plans.

• Improve financial support. First, a proportion of investment subsidies should be given to new geothermal projects or for the replacement of coal-fired boiler projects with geothermal heat sources and primary pipe networks (medium-deep and deep geothermal projects) or heat pump systems (shallow geothermal energy projects). Second, learn from wind and solar energy industry policies and provide subsidies to geothermal project operation.

• Increase tax concessions. First, comprehensively increase the tax concessions for the geothermal industry. Second, focus on optimizing resource tax incentives for the geothermal industry. For example, a fully recycling geothermal heating project is a renewable energy heating project that should be exempted from resource taxes.

• Improve the price mechanism. First, innovate to optimize the price mechanism. Second, adapt to local conditions for improving the heating price mechanism.

• Develop green finance. First, governments at all levels should promptly set up a special fund for geothermal industry development, ensuring that geothermal utilization is included in the scope of special subsidies for renewable energy. Second, strengthen credit support to encourage banks to expand credit coverage and give interest rates that are preferential for geothermal utilization project loans. Third, strengthen business model innovation and promote diverse investment entities.

4.4 WT strategy

The administration system for regulation of the geothermal industry can be optimized as follows:

• Related administration departments and bureaus should jointly negotiate and release administrative measures for the exploration and development of geothermal resources in China. This document should clearly define the legal attributes and designate the department who has the authority for geothermal energy and its administration. At the same time, the requirements should be clearly defined for exploration registration, mining approval, development planning, supervision and inspection, and legal responsibilities.

• Governments at all levels and major bureaus should issue supporting departmental regulations and normative documents on the basis of the administrative measures for full implementation.

• An environment monitoring system should be promptly established with the responsibility of improving industry standards, establishing a commitment and evaluation mechanism, and strengthening the supervision and management of the entire process of geothermal energy projects.

China should establish talent training systems for supporting future geothermal industry growth, providing a guarantee and intellectual support for the rapid development of geothermal industry. The development and utilization of geothermal energy resources involve multidisciplinary skills that are comprehensive and challenging. The geothermal industry urgently needs this talent support system, including the professional training of employees, undergraduate, and postgraduate students.

5 Conclusions

Geothermal resources/energy, which are abundant in the local environment and have huge reserves, can provide free and stable heat from the earth for power generation and heating/cooling. All provinces (regions) in China have invested on the exploration and development of geothermal energy. The annual development and utilization of geothermal resources in China ranks first in the world. However, China's current development of geothermal energy shows a gap with its rich resource potential and growing energy demand.

Surveys indicate that the current geothermal industry experiences various problems. The overall level of utilization in the geothermal industry is relatively low, and the automation and informatization level lags behind other energy industries. Although the geothermal resource base is strong, the exploration ratio is low because of the lack of understanding on resource details. Disconnected administration systems make it difficult to implement cohesive planning. An incomplete policy system makes the stakeholders hesitant to focus on geothermal energy. From the strategic perspective, the disconnected administration and incomplete policy system may be the urgent problems.

We suggested the following top-level design and planning strategies for China's geothermal energy on the basis of SWOT–PEST analysis:

• Pilot and demonstration projects should be implemented following the major national strategies, including Xiong'an New Area and Winter Clean Heating, as a breakthrough to lead geothermal industry development;

• Resources and Geothermal Plus strategies should be intensively utilized and scientific and technological innovation and informatization construction should be enhanced;

• Increase resource exploration and evaluation and improve resource security level;

• Reform geothermal administrative measures to strengthen institutional guarantees;

• Optimize related policies on prices, taxes, and fees and promote the development of green finance;

• The future of geothermal energy industry depends on the utilization of HDR resources. In the future, research should focus on technical, economic, and management issues for the utilization of HDR resources and provide strategic support to their commercial development.

The information statistical system should be improved by integrating different techniques, including on-site surveys, expert interviews, the Industrial Internet, big data analysis, and artificial intelligence, to support the continuous strategic research on geothermal energy in the coming 14th Five-Year Plan.

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