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Opportunities and Challenges for Sustainable Development of Geothermal Energy in China in the New Era

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ABSTRACT

Geothermal energy, as a clean renewable energy, is a “green engine” to optimize the energy structure, protect the ecology, drive the economy and improve people’s livelihood. At present, geothermal industry in China has entered a period of rapid development, with policy support increasing, market demand explodes, technological breakthroughs significantly reduced the development costs, and the industry status steadily improves. However, opportunities and challenges coexist, and the development of geothermal energy in China is also facing the problems such as technical bottlenecks in deep geothermal, Lack of policy and regulatory synergy, market promotion resistance and other practical problems still restrict the large-scale development of the industry. For this reason, this paper systematically combs the "technology-policy-market" three-dimensional collaborative model based on practical cases, aiming to provide a "replicable and scalable model of practice" for the large-scale development of geothermal energy in China. By implementing targeted strategies to break through technical blockages, policy disconnects, and pain points, we aim to activate the potential of geothermal energy, create a "geothermal engine" for China's economic green transformation, inject powerful momentum, and drive the-quality development of Chinese society and economy.

1 INTRODUCTION

Driven by the dual imperatives of global climate change and energy transition, the development and utilization of clean energy has become a central pathway for nations worldwide to achieve sustainable development goals. Geothermal energy, a renewable resource characterized by abundant reserves, wide distribution, and stable supply, has been recognized by the International Energy Agency (IEA) as one of the "most promising green energy sources of the 21st century," owing to its unique advantages including low carbon emissions and integrated power generation, heating, and cooling capabilities. As the world's largest energy consumer, China's long-standing reliance on coal-dominated energy infrastructure has exerted mounting pressure on its ecological environment. Against this backdrop, the large-scale development of geothermal energy not only bears the strategic mission of optimizing the energy mix and reducing carbon emissions but has also emerged as a pivotal driver for promoting regional green economic transformation and enhancing public well-being.

In recent years, China's geothermal industry has entered a phase of rapid development, marked by continuous improvements in the policy support system and explosive growth in market demand. Breakthroughs in key technologies such as deep geothermal drilling and reservoir modification have significantly reduced development costs, leading to steady expansion of the industry's scale and influence. However, practical challenges—including insufficient accuracy in deep geothermal resource exploration, inefficient coordination among policy and regulatory departments, and lagging market awareness and business model innovation—continue to hinder the transition of geothermal energy from "pilot demonstration" to "large-scale application." There is an urgent need to develop systematic solutions to unlock the industry's potential.

This paper addresses the practical challenges facing geothermal energy development in China, adopting a "technology-policy-market" synergy mechanism as the core research framework. By analyzing typical practical cases, it systematically examines the interactive dynamics among technological breakthroughs, policy optimization, and market activation. The study proposes a three-dimensional synergy model aimed at overcoming technical barriers in deep geothermal development, bridging gaps in policy implementation, and breaking through market promotion obstacles to establish a replicable pathway for scaled development. Through targeted strategy implementation, the research seeks to facilitate geothermal energy's role as an "engine" for China's green economic transformation, providing both theoretical support and practical references for optimizing the energy structure and advancing sustainable development.

2 OVERVIEW OF POLICIES AND STRATEGIES FOR SUSTAINABLE DEVELOPMENT OF GEOTHERMAL ENERGY

Against the background of global energy transition and China's "dual carbon" goals, geothermal energy has become an important part of energy structure optimization. A multi-level and coordinated policy and strategy system has been formed at national and local levels, providing institutional guarantee for the large-scale and sustainable development of geothermal energy.

2.1 National Strategic Orientation

Geothermal energy is a key renewable energy for optimizing energy structure, ensuring energy security and supporting the realization of the dual carbon goals. China has included geothermal energy in the priority development of renewable energy to replace fossil energy in heating, cooling, industrial heat and power generation, and set clear development goals in the 14th Five-Year Plan for Renewable Energy Development.

2.2 Core National Policies

The state promotes the standardized development of geothermal energy through top-level design:

- Taking Guoneng Faxing Nenggui〔2021〕No.43 as the core document, it sets goals to increase the national geothermal heating (cooling) area by 50% and double the installed geothermal power generation capacity by 2025, and double the scale again by 2035. It advocates "heat extraction without water withdrawal" and full reinjection of geothermal resources.

- Supporting policies promote the application of geothermal energy in clean heating, heat pump projects and coal mine transformation, and encourage the integrated utilization of geothermal energy with multiple industries.

2.3 Regulatory and Technical Strategies for Sustainable Development

Focusing on resource protection and green development, three core strategies are implemented:

1.Carry out national geothermal resource surveys, improve the resource database and enhance exploration accuracy;

2.Strictly implement same-layer equivalent reinjection and closed-loop heat extraction to protect groundwater and geological environment;

3.Improve the whole-process standards for exploration, drilling and reinjection, and carry out digital supervision of projects.

2.4 Local Differentiated Policies

Local governments implement targeted policies based on regional resource endowments:

- North China focuses on promoting geothermal clean heating;

- Central and western regions with rich resources build geothermal demonstration projects integrating tourism and agriculture;

- Major coal-producing provinces use geothermal energy to promote the green transformation of mining areas.

2.5 Market and Industrial Support Strategies

The economic efficiency of projects is improved through **green finance, tax incentives and reasonable pricing** to encourage the participation of social capital. Meanwhile, the R&D and manufacturing of geothermal equipment are supported to improve the local industrial chain.

2.6 Future Development Direction

Accelerate the introduction of special regulations for geothermal energy and improve the cross-departmental coordination mechanism; achieve breakthroughs in deep geothermal and hot dry rock technologies, and promote the transformation from demonstration projects to large-scale application; expand the "geothermal +" multi-scenario application mode to realize efficient and sustainable development of resources.

3 CURRENT STATUS OF CHINA'S GEOTHERMAL ENERGY INDUSTRY DEVELOPMENT

3.1 Abundant Geothermal Energy Resources

According to data from the China Geological Survey, the total amount of geothermal resources in mainland China accounts for approximately one-sixth of the global geothermal resources, equivalent to about 1.25 trillion tons of standard coal. Among them, the annually recoverable amount of shallow geothermal resources is equivalent to approximately 700 million tons of standard coal, while the annual exploitable quantity of hydrothermal geothermal resources reaches 1.865 billion tons of standard coal equivalent. The reserves of dry hot rock resources at depths between 3,000 and 10,000 meters underground amount to 856 trillion tons of standard coal equivalent, The prospects for its development and utilization are extremely broad. Compared with renewable energy sources such as wind power and photovoltaics, geothermal energy possesses unique advantages. It is not affected by natural conditions such as seasons, climate, or day-night cycles, enabling a continuous energy supply with an average annual operating time exceeding 8,000 hours. From the distribution of the geothermal resources, high-temperature convective geothermal resources are primarily located in Tibet, the Tengchong modern volcanic region, and Taiwan. Medium-temperature and low-temperature convective geothermal resources are mainly distributed in coastal provinces such as Guangdong, Fujian, and Hainan. Meanwhile, medium-emperature and low-temperature conductive geothermal resources are widely distributed the southeastern coastal provinces and inland basin regions.

3.2 Huge Development Potential

According to statistics, that China's installed capacity for geothermal power generation is only 61.47 MW, ranking 19th globally and accounting for just 0.22% of the world's total installed geothermal power capacity. Direct utilization of geothermal energy is primarily for heating, with hydrothermally sourced geothermal energy heating an area of approximately 630 million square meters, and shallow geothermal energy used for heating and cooling covering about 850 million square meters. Other applications such as therapeutic uses, agriculture, and aquaculture follow, indicating a relatively limited scope of utilization. With an installed geothermal power generation capacity of only 61.47 MW, its potential in fields like electricity generation and industrial heating remains underexploited. Furthermore, the uneven distribution of geothermal resources and the difficulties in exploration have restricted their development in some regions. This is particularly true for high-temperature geothermal resources, which are predominantly concentrated in the Qinghai-Tibet Plateau and its periphery. These areas are far from major energy consumption markets, leading to high development costs. Overall, the vast potential of China's geothermal energy resources has not yet been fully unlocked, indicating substantial scope for future development.

4 MULTIPLE CHALLENGES IN GEOTHERMAL ENERGY DEVELOPMENT

As a green, low-carbon, stable, and reliable renewable energy source, geothermal energy holds significant potential for development and utilization in China. However, its current development faces multiple challenges, including "technological bottlenecks, an absent market mechanism, and a lagging regulatory system."

On the technical front, the exploration and development of geothermal resources present significant technical challenges and risks. These resources are typically buried deep underground, requiring specialized exploration technologies and equipment to determine their location, reserves, and quality. At present, China has not yet fully ascertained the full extent of its geothermal resources, and the accuracy of the latest survey data remains insufficient, leading to risks of exploration failure or increased costs. Meanwhile, the drilling costs for geothermal wells are high, with the construction expense of a single well potentially reaching tens of millions or even over a hundred million yuan. Inaccurate exploration could result in substantial economic losses. Furthermore, China faces bottlenecks in deep geothermal technology. While deep geothermal resources offer advantages such as high temperatures and large reserves, their development is difficult. Domestically, there is still a gap compared to international advanced levels in key technologies such as deep geothermal drilling and efficient heat exchange, which restricts the large-scale development and utilization of deep geothermal resources.

On policy level, the development of the geothermal industry still faces some problems such as inadequate management and development policies. Insufficient coordination between policies and regulatory oversight remains a prominent issue. Geothermal energy development involves multiple governmental departments—including energy, natural resources, development and reform, and environmental protection—yet policy

coordination among these agencies remains weak, and regulatory standards are inconsistent. This situation creates numerous obstacles for enterprises in areas such as project approval and operational management. Currently, policies governing geothermal resource management and development in some regions remain underdeveloped, manifesting as complex approval procedures and ambiguous resource ownership rights. Furthermore, the pricing mechanism for geothermal energy lacks rationality. Compared with conventional energy sources, geothermal energy lacks distinct price advantages, which to some extent undermines its market competitiveness.

On the market front, the development of the geothermal industry requires substantial capital investment. Each stage - from resource exploration and development to utilization - demands significant financial support. For small and medium enterprises and projects, financing difficulties constitute a major constraint on their development. Furthermore, the geothermal industry characteristically has long investment return cycles, typically requiring several years or even decades to recoup costs, which consequently dampens corporate investment enthusiasm.

5 DEVELOPMENT STRATEGY BASED ON THE "TECHNOLOGY-POLICY-MARKET" SYNERGY MODEL

5.1 Strengthen the research and innovation of key geothermal technologies to improve the efficiency of resource utilization

Strengthening the research and innovation of key geothermal energy technologies is the core driving force to improve the efficiency of resource utilization and promote the sustainable development ofothermal energy. At present, China's geothermal sector faces significant technological bottlenecks, with particularly notable deficiencies in deep geothermal resource exploration, drilling technology, and efficient utilization, which collectively constrain the large-scale development and application of geothermal energy. By intensifying fundamental research and making breakthroughs in critical technologies, the efficiency of both geothermal resource development and utilization can be substantially elevated.

Specifically, the primary focus should be on achieving technological breakthroughs in geothermal resource exploration and evaluation. Currently, deep geothermal resources present complex geological structures and uneven distribution, making exploration particularly challenging. The introduction of advanced seismic exploration technologies, heat flow measurement methods, and artificial intelligence algorithms can significantly improve exploration accuracy and reduce development risks. Secondly, developing efficient geothermal drilling technologies is crucial. The exploitation of deep geothermal resources requires drilling equipment and materials capable of withstanding extreme temperatures and corrosion, while also addressing operational challenges such as pipe sticking and fluid loss during drilling processes. Furthermore, technological advancements in geothermal power generation represent another critical direction for enhancing resource utilization efficiency. Given the relatively low conversion efficiency of high-temperature geothermal resources in power generation, significant improvements can be achieved through optimized turbine design and enhanced steam utilization efficiency.

Meanwhile, innovation in cascade utilization technology for geothermal energy requires enhancement. For instance, utilizing waste heat from geothermal power generation for diversified applications such as agricultural greenhouse heating and industrial drying can achieve full-chain, high-efficiency resource utilization. Furthermore, promoting "heat extraction without water withdrawal" technology—extracting geothermal energy through closed-loop circulation systems without depleting groundwater resources—can effectively protect aquifers while enabling sustainable development.

5.2 Accelerate the Improvement of Geothermal Energy Policy Framework to Promote Standardized Industry Development

Accelerating the enhancement of the geothermal energy policy framework and promoting standardized industry development are crucial for achieving sustainable growth in this sector. Currently, China's geothermal energy development still faces challenges such as an incomplete policy system, inadequate management mechanisms, and inconsistent market access standards. There is an urgent need to drive healthy industry progress through institutional innovation and policy optimization.

First, establish a comprehensive legal and regulatory framework for geothermal development. This requires clearly defining ownership rights, usage rights, and benefit distribution mechanisms for geothermal resources, while standardizing approval procedures and regulatory oversight.

Second, enhance digital management of geothermal projects through a unified national platform. This system should cover project registration, operational monitoring, and data statistics, enabling full-process digital management and providing robust data support for scientific decision-making.

Third, formulate differentiated development policies tailored to regional resource characteristics and energy demand. Avoiding one-size-fits-all approaches will promote efficient utilization of geothermal resources based on local conditions.

Fourth, strengthen technical standards and specifications covering the entire development cycle. Standards should be established for exploration, drilling, heat exchange, and reinjection processes to improve operational standardization and quality control.

Fifth, improve market supervision mechanisms to ensure fair competition and sustainable development. This involves creating a level playing field for private capital participation while strengthening qualification reviews for developers and quality oversight of projects.

5.3 Promote Coordinated Development of Geothermal Energy and Regional Economies to Achieve Green Transition

Fostering synergistic development between geothermal energy and regional economies serves as a crucial pathway toward green transformation. As a clean, low-carbon, and stable renewable energy source, geothermal energy offers significant environmental and economic benefits, injecting new vitality into regional economic development. Within the context of the dual carbon goals, this coordination not only helps optimize the energy structure but also drives the green and low-carbon transition of the economy, contributing to the achievement of sustainable development objectives.

Firstly, geothermal energy development can drive the extension of regional industrial chains and stimulate employment growth. A prime example is Shandong Province, where the promotion of geothermal heating and cooling projects has not only optimized the local energy mix but also fostered the growth of related industries, including geothermal equipment manufacturing and engineering construction. These initiatives have generated substantial employment opportunities. According to available data, clean heating projects in northern China alone have catalyzed the formation of an industrial cluster with an annual output value exceeding hundreds of billions of yuan, providing robust support for regional economic development.

Secondly, the multi-scenario application of geothermal energy creates diversified development opportunities for regional economies. Shallow geothermal energy can be utilized for building heating and cooling, mid-deep geothermal resources for industrial drying and agricultural greenhouse heating, while high-temperature geothermal resources are suitable for power generation and hot spring wellness tourism. This "multi-purpose cascade utilization" model not only enhances resource efficiency but also fosters diversified regional economic development. For instance, in Dali, Yunnan Province, the integration of geothermal power generation with agricultural greenhouses has expanded application scenarios, achieving synergistic development between energy and agricultural sectors.

Furthermore, the regional synergistic development model of geothermal energy offers innovative pathways for green transformation. Through the establishment of demonstration zones and the dissemination of successful practices, geothermal development can create replicable and scalable models. A notable example is Shandong Province, where designated geothermal demonstration zones have promoted the integrated utilization of geothermal resources with tourism, agriculture, and aquaculture, providing valuable experience for other regions. Simultaneously, geothermal energy development can drive regional infrastructure improvement and industrial upgrading, thereby enhancing the overall competitiveness of regional economies.

6 PRACTICAL CASE ANALYSIS

6.1 Case 1: Dali Geothermal Hot Spring Resort Project in Yunnan Province

Eryuan County is endowed with abundant geothermal resources, characterized by wide distribution and substantial reserves, making them one of the county’s key advantages. The Dali Geothermal Hot Spring Resort Project spans an area of 1,000 mu, with a total investment of 347 million yuan, and functions as a leisure tourism resort specializing in hot spring bathing culture. The geothermal water at the resort maintains temperatures between 70°C and 90°C and is rich in trace elements such as potassium, calcium, magnesium, and iron, offering notable therapeutic and health benefits.

Through the synergistic integration of technology, policy support, and market demand, the Dali Geothermal Hot Spring Resort Project in Eryuan County has achieved efficient resource utilization and industrial upgrading:

Technologically, the project leverages Eryuan's high-capacity geothermal resources, which boast a daily extractable volume of over 10,000 cubic meters and temperatures exceeding 70°C. It employs a closed-loop heating system that channels geothermal water to energy storage tanks in agricultural facilities. Through heat exchangers, the system warms circulating pipelines to provide heating for agricultural greenhouses. Simultaneously, the project has developed diversified wellness offerings such as hot spring baths, herbal pools, and milk baths, enabling cascaded utilization of energy.

Policy-wise, the project aligns with the vision outlined in the Eryuan County 14th Five-Year Plan for National Economic and Social Development and Long-Range Objectives Through 2035*, which aims to "build a renowned hot spring wellness and tourism destination." It has received policy support from the county government in areas including land use approval, financial subsidies (such as support under binding tasks in agricultural development funds), and ecological protection (e.g., groundwater pollution prevention and supervision). Additionally, the project has been designated as a pilot for geothermal resource development in Dali Prefecture, qualifying for specialized exploration and development support.

Market demand has been a key driver. The project capitalizes on the growing trend of wellness tourism, targeting employee rehabilitation and leisure markets. It offers comprehensive facilities such as 156 exclusive guest rooms, professional kitchens, fitness centers, and partnerships for traditional Chinese medicine therapies. By integrating elements like "hot springs + intangible cultural heritage" and "hot springs + rural tourism," the project not only provides high-quality hot spring experiences but also boosts local tourism, establishing itself as a signature attraction in Eryuan County.

6.2 Case 2: Ningbo Shenzhen Town Geothermal Development Project

The Ningbo Shenzhen Town Geothermal Development Project has achieved efficient resource utilization and industrial upgrading through the synergistic integration of technological innovation, policy support, and market demand. This trilateral collaboration encompasses: Technological Breakthroughs: Adoption of "high-precision geophysical exploration + specialized drilling techniques"; Policy Support: Implementation of "resource-specific planning + dynamic mining rights allocation"; Market-Driven Applications: Development of "hot spring therapy + forest wellness + low-carbon heating" services.

Technological Innovations: The project employed advanced geophysical methods—including transient electromagnetic, controlled-source audio-frequency magnetotelluric, and geoelectric lithology detection—to accurately locate thermal reservoir aquifers below 1,500 meters. Combined with specialized drilling techniques, it overcame challenges posed by hard volcanic rock formations and high water levels in the Jurassic strata. The achieved output—water temperature of 65°C and a flow rate of 71.7 tons per hour—represents the highest performance recorded for geothermal wells in Zhejiang Province.

Policy Framework: Aligned with the Special Plan for Geothermal Resource Exploration and Development in Ninghai County, the project benefited from government-led resource assessment and dynamic mining rights management. The "China Hot Spring Town" designation further facilitated standard setting and industrial clustering, creating an enabling environment for large-scale development.

Market Applications: Centered on hot spring-based wellness, the project expanded into forest retreats and low-carbon heating solutions. Notable developments include the "Naked Spring Hot Spring Resort" and "Da zhuang Valley · Hometown Roots" project. The latter, with an investment of 3 billion CNY and covering 2,105 mu, has generated cumulative tourism revenue of 578 million CNY and created over 3,000 jobs. This success demonstrates a virtuous cycle of "resource development → industrial diversification → market feedback."

7 CONCLUSION

Looking ahead, with continuous technological advancements, ongoing policy refinement, and gradual market cultivation, China's geothermal energy industry is poised to embrace broader development prospects.

Technologically, breakthroughs in deep geothermal technologies are anticipated to enable the efficient development and utilization of deep geothermal resources.

Policy-wise, a more comprehensive and coordinated policy system is expected to take shape, providing robust support for the industry's growth.

Market-wise, the application domains for geothermal energy will continue to diversify, driving sustained growth in market demand.

Concurrently, China's geothermal sector will strengthen international cooperation and exchange, actively participating in the global effort to develop and utilize geothermal energy. This engagement will contribute significantly to the global energy transition and the collective response to climate change.

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