PROCEEDINGS, 43rd Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, February 12-14, 2018
SGP-TR-213

An EGS Site Evaluation Method for Geothermal Resources Based on Geology, Engineering and Economic Considerations

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Keywords: geothermal resource, Hot Dry Rock, Enhanced Geothermal System, EGS Site Evaluation method

ABSTRACT

Site screening is one of the most crucial factors in the ultimate success of EGS (Enhanced Geothermal System) resource exploration. It should cover key project factors such as the geothermal gradient, reservoir temperature, water-storage capacity, and water-bearing condition in the reservoir rocks. During the technical and economic evaluation of geothermal resources, middle-to-deep geothermal resources can be classified as either hydrothermal or HDR (Hot Dry Rock). The former involves fluid-bearing reservoirs with excellent or poor storage capacity, while the latter consists of the following reservoir types: HDR with excellent storage capacity, HDR with poor storage capacity, and HDR with no storage capacity. Of these reservoir types, inferior fluid-bearing reservoirs, HDR reservoirs with excellent storage capacity, and HDR reservoirs with poor storage capacity are the most suitable for EGS exploration and development. The quantities of these five natural geothermal resources can be arranged into a pyramid-like structure, wherein the technical difficulty of resource exploration increases from top to bottom. Based on geological resources, engineering technology, and economic considerations, an evaluation method has been proposed for EGS site screening and the identification of key indexes by combining tri-factor analysis and multi-tiered index calculations.

1. HDR AND EGS CONCEPTS AND HISTORY OF STUDY

1.1 The definition and evolution of HDR and EGS

In the geothermal resources geologic exploration standard (GB/T 11615-2010) （The National P.R., 2010）, a geothermal resource is defined as geothermal energy, fluid, and other useful components of the Earth's interior that can be utilized economically. Presently, available geothermal resources include natural geothermal springs, shallow geothermal energy extracted by ground source heat pumps, geothermal fluid accessed directly through a borehole, and geothermal energy in Hot Dry Rock (HDR) formations. The EGS (Enhanced Geothermal Systems) concept, which includes HDR, originated at the Los Alamos National Laboratory (LANL) in the USA. The technique was set out in a patent filed in 1974 by Brown that defined HDR as rock that has a natural temperature above 200 °C, is without fluid or fractures, and exists at a depth of approximately 2-3 km (Los Alamos National Lab., 1982). In 1976, Muffler classified HDR as a type of geothermal resource (Muffler, 1979). The hot rock in the Hijori area of Japan, which features a depth of 1 km and temperatures exceeding 200 °C, developed structural fractures and fluid-containing micropores as a result of plate activities; this geothermal system is considered to be a transitional system somewhere between HDR and hydrothermal and is therefore classified as Hot Wet Rock rather than HDR. Similarly, the >200 °C 2-3 km-deep hot rock in Soultz, France features structural fractures and micropores without fluid, and is excluded from the HDR classification. In an Australian "HDR" project, the rock was fractured artificially to produce a fracture system called Hot Fractured Rock. Swiss scientists regard these rock formation types as Deep Heat Mining. Japanese scientists Ryokichi and Yoshinao, along with Baria and Garnish in Europe, studied HDR in Japan and Soultz, France, respectively, forming a consensus that the definition of HDR should be less strict and that rock satisfying some of the given conditions can be classified generally as HDR; for instance, rock with a temperature exceeding 200 °C, suitable burial depth (usually deeper than 1 km), and little or no fluid content may be classified as HDR (Morton, 1983). In the 21st Century, the term 'HDR' evolved gradually to represent impermeable, hot rock without fluid or steam that resides at a belowground depth between 3 km and 10 km and contains temperatures between 150 °C and 600 °C. Li et al. (2015) stated that HDR should be defined from separate broad and narrow perspectives; the former considers HDR objectively and scientifically (as opposed to economically and practically) as a type of heat-reserve rock with little fluid and holding a temperature between 150 °C and 400 °C. The narrow perspective regards HDR through the lens of geothermal energy exploitation, considering the economic and practical facets of geothermal electricity generation; this might include, for example, solid or half-solid hot rock with low-fluid rheological activity buried between 3 km and 8 km and containing higher temperatures between 200 °C and 350 °C. The definition of HDR used herein generally agrees with the definition set out by Japanese and European scholars, which does not follow the strict definition proposed by Brown (in 1974) and states that HDR should be impervious, contain no fluid, and have a natural temperature higher than 200 °C.

It is commonly agreed that in order to achieve economical and effective HDR development, the wellhead flow for EGS thermal wells should be at least 80 L/second; this value represents an economic threshold regarding cost recovery for drilling and reservoir reconstruction. In areas with no natural pore systems, where fluid flow relies completely on the channel networks generated by artificial fracturing, it is early impossible to achieve commercial-scale production. Even if sufficient fluid flow is achieved, the cost of drilling and reservoir reconstruction is untenable. Therefore, in addition to high temperature (higher than 200 °C), reasonable burial depth (usually greater than 1 km), and the absence of significant amounts of fluid, HDR also must have certain reservoir properties, such as excellent thermal capacity. The effective development of HDR technology depends upon the discovery of high-quality HDR reservoirs that meet these very specific criteria.

EGS is an important method for HDR resource exploitation. The acronym first referred to 'Engineering Geothermal Systems' before the community ultimately settled on 'Enhanced Geothermal System.' The EGS concept originated in a heat-extraction experiment at Fenton Hill, west of Los Alamos, New Mexico, USA in the 1970s and refers to special engineering technology in which the rock reservoir properties are improved and/or low-temperature fluid is injected into the reservoir for the effective exploitation of geothermal resources. These techniques are performed at great depth via boreholes. One type of borehole, the injection well, is used to inject low-temperature fluid into the earth. This fluid absorbs heat as it passes through the rock and is returned to the surface via one or more 'production well' boreholes. The rock mass through which the water passes in order to extract heat acts as a heat exchanger and is known as a reservoir. The extracted heat can be used for heating buildings, industrial processes, and/or electricity generation. According to the MIT (Massachusetts Institute of Technology) monograph The Future of Geothermal Energy: Impact of Enhanced Geothermal Systems (EGS) on the United States in the 21st Century (Tester et al., 2006), EGS is poised to dominate future geothermal energy utilization through the use of geothermal resources such as HDR, Hot Wet Rock, and Hot Fractured Rock; also, the recoverable U.S. EGS resource measures more than 20 × 104 EJ, which is roughly 2000 times the current annual primary energy consumption in the United States. In this treatise, EGS is described as replacing HDR, which could lead to resource-type misunderstandings, and the EGS definition remains broad and essentially useless.

HDR is merely a geothermal resource, while EGS represents a comprehensive heat-extraction method through artificial reservoir-reform technology; these terms should not be confused or used interchangeably.

1.2 The study of HDR and EGS

HDR resources have been discussed extensively worldwide for their vast resource base, which exceeds that of other energy sources, and low environmental and carbon impacts. Developed countries such as the USA, UK, Australia, Germany, and Japan have evaluated HDR resources in their nations (Bendall et al., 2014; Genter et al., 2010; Julio, 2013; Olasolo et al., 2016; Patrick, 2013; Zigro et al., 2013); in the continental USA, for example, the HDR resource featuring 3 km to 10 km depth and a temperature exceeding 150 °C is estimated to be equivalent to 500 trillion tons of coal.

EGS may be the most effective method for HDR exploitation. HDR heat-extraction technology is expected to develop rapidly in the near future; however, few large-scale HDR projects are currently run commercially. The overall goal of the EGS Program is to demonstrate the commercial feasibility of geothermal energy derived from HDR. The principal objectives, therefore, are 1) to confirm the size and accessibility of potential HDR resources, 2) to develop a commercially viable technology base for extracting the energy therefrom, and 3) to evaluate whether the environmental and social consequences of HDR development are acceptable.

Since the 1970s, many countries, and notably the USA, have launched various on-site EGS projects on HDR resource exploitation that have yielded extensive practical knowledge; useful lessons have also been learned from EGS failures. Between 1970 and 1990, six on-site HDR exploitation test projects were launched successively in the USA, UK, Japan, Sweden, and France. HDR development then lagged, with no new projects launched between 1991 and 2000. Since 2001, however, investment in and study of HDR have rebounded remarkably, with numerous new EGS project launches in the USA, Germany, Australia, Switzerland, and South Korea demonstrating the acceleration in EGS study and on-site testing.

The geological settings targeted for on-site EGS testing abroad include plate boundaries (e.g., Hijori and Ogachi in Japan, which are near craters), transform fault systems (e.g., the Geysers in the USA), intra-continent crustal thinning zone (e.g., the EGS projects in France, Germany, and Switzerland in the Upper Rhine Graben), and intracontinental areas with radioactive granite (such as the Australia Habanero project in the Cooper basin; Figure 1). The reservoir rock types targeted for EGS testing are dominated by granite, some volcanic rocks, metamorphic rocks, and sedimentary rock. In the early stages of on-site EGS testing (1970−1990), the test area was usually located at some distance from conventional hydrothermal fields; more recently (2000 to present), testing has been conducted at the edge of or just inside the conventional hydrothermal field area. To date, four experimental EGS projects have successfully generated electricity, including the US Desert Peak project, the Australian Habanero A project, the French Soultz project (energy from which is distributed on the French national grid), and the Japanese Hijori project. Further, the Geysers project in the USA produces dry steam for electricity generation, and the German Landau project unites electricity generation and space heating (Table 1).

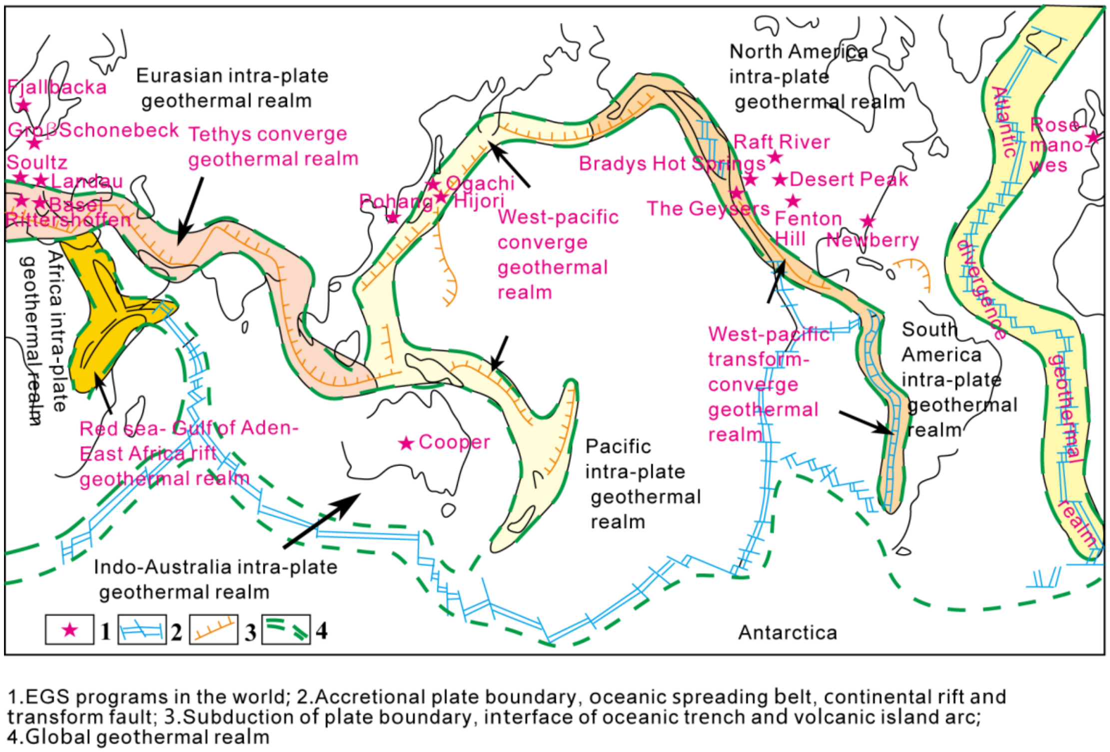

Figure 1: Global geothermal realm and the distribution of on-site EGS testing

Table 1 A brief introduction to major EGS projects worldwide

Project	Duration	Reservoir	Temperature (°C)	Depth (m)	Flow (L/s)	Relationship with Hydrothermal Field	Test Outcome	Present installed capacity (MW0
Fenton Hill, USA	1970–1995	Granite	317	4391	13	Outside	Showed that heat-extraction technology is practicable.	0
Desert Peak, USA	2001–2013	Metamorphic rock	~135– 204	1525 – 2475	100	In Desert Peak hydrothermal field	Joined national grid in April 2013, generates 1.7 MW.	1.7
The Geysers, USA	2009–Present	Greywacke	347	2600	9.7	In NW area of the Geysers geothermal field	Produces dry steam; has a generating capacity of 5 MW.	5
Habanero A, Australia	2009–2013	Granite	270	4911	19	Outside	Generated successfully on April 30th 2013; pilot run for 160 days at 1 MW capacity.	0
Soultz, France	1987–Present	Granite	200	4950	25	Outside	Began generating in 2011; has a capacity of 2.5 MW.	2.5
Landau, Germany	2003–Present	Carbonate rock	160	3000	76	Outside	Output potential is 5 MW; 3 MW are actually generated.	5
Hijori, Japan	1981–1986	Granite	270	2200	12.8	Outside	Experimental electricity generation concluded.	0

Compared to other nations, China began its study of HDR after 2000 (Ran et al., 2010; Lin et al., 2012; Yang et al., 2012; Zeng et al., 2012; Jiang et al., 2013; Zhai et al., 2014; Zhang et al. 2015; Liu, 2016; Wang, 2016; Wang et al., 2016). Recently, various institutions and academics have undertaken preliminary evaluations of HDR resources in China and drilled a small number of HDR exploration boreholes (Wang et al., 2012; Lou et al., 2014). EGS-related experiments and numerical simulations have been performed concurrently to some extent; however, on-site EGS tests are still infeasible at present. According to the most updated HDR resource evaluation by the

China Geological Survey (Wang et al., 2016), China's continental HDR resources at depths between 3 km and 10 km and with temperatures exceeding 150 °C are equivalent to 856 trillion tons of coal and are distributed widely through southern Tibet, western Yunnan, western Sichuan, the southeastern coast, the Bohai Bay area, and the Fenwei Graben.

The primary tasks in the development of HDR via EGS include: 1) large-scale site screening based on geological risk analysis and resource, technology, and economic evaluations; 2) gaining approval for exploration of the selected target areas; and 3) beginning on-site testing to explore the practicability of large-scale HDR development. EGS site screening is one of the most crucial factors in EGS project success. Therefore, the methods used to select appropriate target areas for EGS experiments will play a decisive role in China's large-scale commercial HDR development in the near future. Consequently, this paper focuses on screening methods for establishing EGS target sites based on experiences and lessons from EGS site testing and HDR resource characterization abroad.

2. A DISCUSSION OF HDR CONCEPTS AND FUNDAMENTAL GEOTHERMAL RESOURCE TYPES

Researchers worldwide have expressed great optimism over the potential of HDR resources (Tester et al., 2006; Hal, 2013; Zheng et al., 2014; Lu et al., 2015; Singh et al., 2015); however, we must ask why, given this potential, HDR resource have not been developed commercially in the intervening decades. It is not clear whether HDR development is thwarted by resource, technology, or economic limitations, but these pivotal factors require serious consideration.

Site selection methodology was discussed during the exploration and development of unconventional shale oil and gas. However, the concept was not applied specifically during the successful development of unconventional oil and gas in the United State and other countries. Development efforts focused on finding and characterizing the "sweet spot" while gradually establishing and perfecting the necessary technology and continuously reducing costs. These processes resulted in a shale oil and gas revolution. As an important unconventional geothermal resource, the development and utilization of HDR can draw from the successful development of shale oil and gas, following a similar technological development pathway to find geothermal "sweet spot"; this approach could result in the development of low-cost, high-efficiency drilling technology, the gradual optimization of production technology, and the development of operational processes appropriate for the effective utilization of these vast energy resources.

In order to address resource, technological, and economic considerations in this geothermal development project, we classified deep-layer geothermal resources as either hydrothermal or dry hot rock, which are related but distinct. In general, geothermal systems in the middle- and deep layers have three major attributes: temperature, water content, and reservoir type (Figure 2). Conventional hydrothermal systems, which feature high temperature, abundant water resources, and excellent reservoir permeability, comprise the most effectively developed geothermal resources at present; conventional hydrothermal systems are among the best geothermal resources due to their water content and excellent storage capacity. In addition, there are less-ideal hydrothermal systems that feature high temperature and abundant water supply but lack permeable or compact reservoirs. Because this kind of hydrothermal system produces little hot water or steam, it is not suitable for economical development using conventional methods; more advanced technology is needed to increase production. Therefore, these types of reservoirs are considered to be non-conventional geothermal resources and can be included in the EGS category, in which efficient drilling methods and reservoir reconstruction are used to increase thermal reservoir pore permeability and realize effective development.

Geothermal systems with little or no enclosed geothermal fluid in the geological body and temperatures higher than 150 °C are defined as dry rock, which is an unconventional geothermal resource. These resources can be further divided into three categories based on heat storage and permeability: HDR with excellent storage capacity, HDR with poor storage capacity, and HDR with no storage capacity. The first two types feature easy reconstruction and/or fluid supplementation and can therefore be incorporated into EGS exploration. In HDR with no water or storage capacity (i.e., hot dry rock in the narrow sense), it is technically difficult to implement cost effectively large-scale reservoir transformations. Therefore, we do not recommend the inclusion of this resource in EGS.

The sizes of the two major geothermal resource categories and five resource subtypes can be arranged in a roughly pyramidal shape (Figure 2). At the top are geothermal resources with water and excellent reservoir capacity; these resources are the easiest to develop and deliver the best economic return, but are the most limited in amount. At the bottom are the abundant HDR geothermal resources with no water or storage capacity; these are the most difficult to develop and have the lowest economy. Under current economic and technical conditions, the middle three categories should be the focus of EGS project development.

For HDR geothermal systems without water and with excellent reservoir conditions, the direct injection of fluid or use of small-scale production improvement measures are sufficient for development as conventional hydrothermal systems. Therefore, they are the first choice for EGS projects. The HDR in the Geysers geothermal field EGS project in the United States has natural fractures for reservoir modification and fluid injection; it belongs to HDR category without water and with excellent reservoir capacity (Jonny et al., 2016; Julio et al., 2016).

Hydrothermal systems with poor storage capacity with or without water are also suitable for EGS development. Because these two geothermal reservoir types have a certain reservoir capacity, their reservoir layers can be reconstructed to form artificial reservoirs with high permeability. In the absence of natural fluid injection, fluid can be artificially injected and heated in the reservoir, and the hot fluid can then be collected for use. These two resources types have been successfully developed in EGS projects such as the Landau project in Germany and the Soultz project in France (Albert, 2013; Eva et al., 2015; Günter et al., 2015). The geothermal reservoir in the dry hot rock pilot project in Landau, Germany is a carbonate rock, which is easy to reform and has achieved reasonable experimental results.

To summarize, the selection of HDR regions for EGS projects in China should give preference to simple, easily developed resources. Priority should be given to resources with high temperature, well-developed reservoir pores and fractures, excellent permeability, and excellent technical and economic conditions. It is highly desirable to develop a pilot zone for artificial hydrothermal geothermal systems, including stable injection and production operations, as early as possible. This pilot will provide the experience and technology necessary for the large-scale economic development of HDR resources.

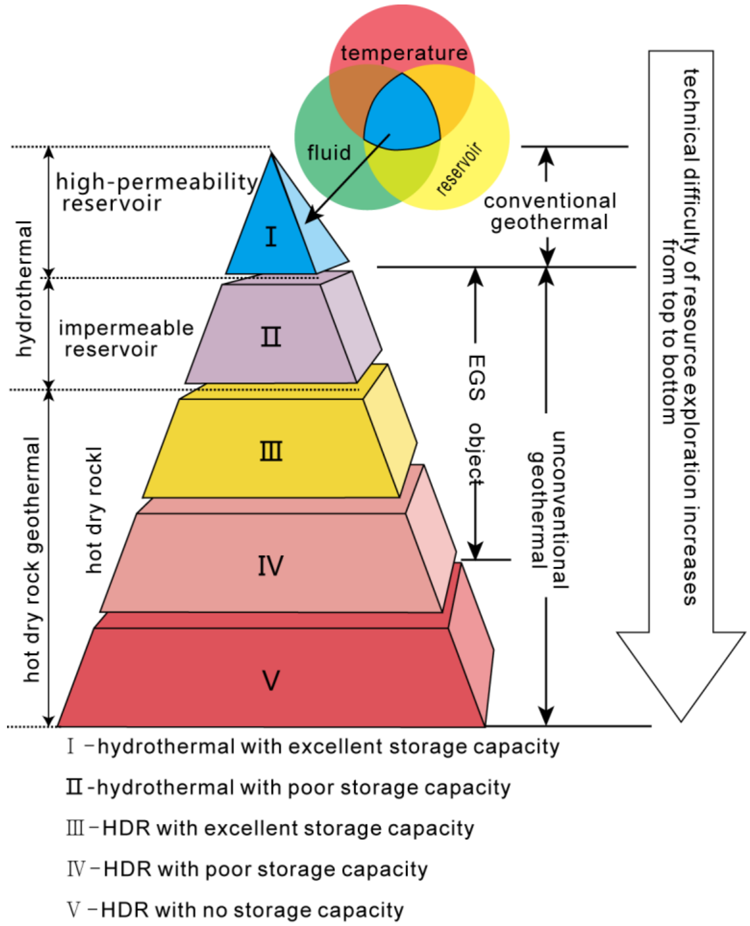

Figure 2: Distribution of geothermal resources and their range of applicability in EGS

3. EVALUATION PARAMETERS AND METHODS FOR EGS PROJECT SITE SELECTION

In China, research and development related to EGS has just begun. Among the many aspects that must be considered, EGS test project site selection remains key and is thus the focus of this study. In recent years, experts in relevant disciplines have proposed various index systems and guidelines for HDR areas (Li, 2010; Zheng et al., 2014; Lin et al., 2015; Ma et al., 2015; Zhuang, 2015). In the oil and gas industry, the selection of exploration areas and target evaluations is an important basic task. After a long history of exploration and data accumulation, relatively complete exploration methods and parameter systems have been developed. In this paper, we develop a set of evaluation methods for EGS project site selection based on those used in the oil and gas industry and considering the unique characteristics of HDR resources and EGS projects.

3.1 Site selection evaluation

In order to realize the large-scale, economical, and effective exploitation of geological resources, it is necessary to consider the resource, technological, and market conditions of projects as well as their geological suitability. After comprehensive analysis of the geological conditions, project advancement, and operations in EGS site projects outside China, we believe that geothermal gradient and temperature are the most important EGS site evaluation factors (Steffen et al., 2015; Albert, 2016; Mahmood et al., 2016); that is, preference should be given to shallow reservoirs with high temperatures. In addition to temperature, reservoir and caprock conditions are also important. Engineering conditions and market conditions affect the successful development and operation of EGS systems and the effective and economic use of the geothermal resources produced. Therefore, multiple parameters are needed to select HDR sites, including information on geological resources, engineering technology, and economic and market conditions. In this paper, three-factor analysis and multi- tiered index methods are used to establish an evaluation method for EGS sites based on resource, engineering, and market circumstances.

3.2 Main parameters and values

3.2.1 Geological resource conditions

Geological conditions include the depth, temperature, lithology, caprock thickness, and fault development of the thermal reservoir and may be divided into two categories: reservoir conditions and caprock conditions.

Geothermal reservoirs with high geothermal gradients are of great importance for conducting EGS projects, but the reservoir should not be too shallow or too deep. Shallow reservoirs (< 1000 m) either do not meet the requirements for HDR resource development or generally feature poor resource preservation, while deep reservoirs (> 5000 m) often possess poor reservoir permeability due to high lithostatic pressure and are limited by difficulties in drilling and reservoir construction and greatly increased cost. In most foreign EGS projects, the geothermal temperature is above 200 °C; only a few projects have temperatures between 150 °C and 200 °C. For artificial reservoir projects, reformation outcomes will vary depending on the natural pore and crack structure in the thermal reservoir; reservoirs with different lithology are reformed differently. Rocks with natural fractures and/or pores are easier to fracture or acidize to construct artificial reservoirs than those without. In addition, the thickness of the caprock and the extent of fracture development play important roles in the preservation of temperature in the reservoir and the stable operation of the fluid circulation system after the completion of construction.

The temperature profile with depth in the geological body is an essential factor used to determine whether sites are selected for EGS projects. The measurement of underground temperature is difficult and has posed a persistent problem for the industry. To avoid blind drilling in sites where the temperature is not high enough for EGS, it is necessary to be able to take underground temperature data at the site or nearby. If these data are not available, the temperature should be calculated based on geothermal gradient and geothermal heat flow data. It is important to confirm the underground temperature, as the measured and calculated temperatures often differ.

Table 2 Evaluation parameters for sites in hot dry rock areas

Parameter			Range (p)		
			1≥p≥0.75	0.75>p≥0.5	0.5>p≥0
Resource condition	Geothermal reservoir	Depth (m)	~1000−4000	~4000−6000	<1000 >6000
		Temperature (°C)	≥ 200	150−200	<150
		Property	Pore or fracture developed	Pore or fracture development unknown	Pore or fracture not developed
		Lithology	Not difficult with current technology	Difficult with current technology	Very difficult with current technology
	Caprock	Thickness (m)	≥ 1000	~500−1000	<500
		Fracture development	Fracture not developed	Fracture slightly developed in the middle	Fracture developed across the caprock
Engineering conditions		Drilling	Not difficult with current technology	Slightly difficult with current technology	Very difficult with current technology, needs major improvement
		Reconstruction	Not difficult with current technology	Slightly difficult with current technology	Very difficult with current technology, needs major improvement
		Operation	Completely supported	Generally supported, needs improvement	Not supported, needs new construction
Market condition		Geothermal demand	High demand, government support	Equal demand, unclear government support	Low demand, rejected by government
		Economy	Unit price higher than coal	Unit price equal to coal	Unit price lower than coal

3.2.2 Engineering conditions

Site construction and related supporting conditions should be considered. The development of HDR resources requires high-temperature drilling technology, testing technology, reservoir reconstruction technology, and geophysical monitoring technology. Professional and technical management personnel are also needed for EGS project construction and operation.

3.2.3 Economic and market conditions

Geothermal resources are currently relatively economically disadvantageous, and the value of geothermal resources varies greatly in different target markets. HDR engineering projects require enormous investments and are technically difficult; they will be profitable and sustainable only when excellent market and economic conditions are available.

We have established a preliminary evaluation system for site selection in HDR areas that considers resource, engineering, and market conditions (Table 2).

3.3 Calculation of parameters and the selection of favorable areas

Primary area selections are assigned parameter vales based on Table 2. The geometric average method was used to calculate the conditional coefficients for different evaluation parameters. The conditional coefficients are calculated using Eq. (1), and the resource, engineering, and market parameter values are calculated using Eq. (2), Eq. (3), and Eq. (4), respectively.

$$T_{condition} = \sqrt[3]{P_{resource} \times P_{engineering} \times P_{market}} \quad \text{......................} \quad (1)$$

$$P_{resource} = \sqrt[2]{P_{reservoir} \times P_{caprock}} \quad \text{......................} \quad (2)$$

$$P_{engineering} = \sqrt[3]{P_{drilling} \times P_{construction} \times P_{operation}} \quad \text{................} \quad (3)$$

$$P_{market} = \sqrt[2]{P_{demand} \times P_{economy}} \quad \text{......................} \quad (4)$$

The parameters for reservoir condition and caprock condition in the resource condition parameter are calculated using Eq. (5) and Eq. (6), respectively.

$$P_{reservoir} = \sqrt[4]{P_{depth} \times P_{temperature} \times P_{feature} \times P_{lithology}} \quad \text{..............} \quad (5)$$

$$P_{caprock} = \sqrt[2]{P_{thickness} \times P_{fault}} \quad \text{......................} \quad (6)$$

The evaluation parameters are then ranked from large to small according to the conditional coefficients; sites with high ranks are favorable for EGS development.

4. CONCLUSIONS

Middle and deep geothermal resources can be categorized as hot hydrothermal, HDR, or any of five subtypes (featuring increasing developmental difficulty) based on resource, engineering technology, and economic considerations. Geothermal systems with high temperatures, abundant water, and excellent reservoir permeability are characterized as aquatic reservoirs with excellent storage capacity. Hydrothermal resources with water and poor storage capacity (or 'unconventional' geothermal resources) can also be included in EGS development.

HDR can be further divided into three categories: HDR with excellent storage capacity, HDR with poor storage capacity, and HDR with no storage capacity; the last type is technically difficult to adapt cost-effectively for large-scale reservoir transformation and therefore is not recommended for EGS development.

Using three-factors analysis and geological resources, engineering technology, and economic and market conditions, a multi-indexing system is established to evaluate site selection for dry rock EGS projects. As a result, factors affecting the key selection indexes for EGS pilot project areas are identified and can be used for EGS HDR project site evaluation in China.

ACKNOWLEDGEMENTS

We thank Professors Wang Jiyang, Cao Yaofeng, Li Kewen, Pang Zhonghe, Hu Shengbiao, and Wang Guiling for their valuable suggestions and comments during the research and writing processes. This work was supported by the Joint Petrochemical Fund from the National Natural Science Foundation of China (Grant No. U1663209)

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