Assessing High Temperature Geothermal Resource - An Economic and Environmental Perspective

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Abstract – *High-temperature geothermal energy is a renewable energy that can be used for generating electricity. In this study, the volumetric method was used to evaluate geothermal resources in combination with the geothermal resource investigation and the evaluation results were used to calculate the high-temperature geothermal resource potential in China, and the economic and environmental perspective of high-temperature geothermal resources were predicted. The results showed that high-temperature geothermal resources are very abundant in China, with total reserves of 10-20 billion tons (t) of standard coal; can produce economic benefits of 60 billion USD/year (y); and can lower CO2 emissions by 1.19 billion tons. High-temperature, hydrothermal-type geothermal resources are an efficient, stable, safe, clean, and renewable source of energy. To increase the intensity of resources exploration, drilling, power conversion, groundwater recharge, and anticorrosion technology innovation is needed to ensure an energy revolution.*

Keywords – economic and environmental perspective, geothermal resource potential, high-temperature, hydrothermal-type, renewable energy.

1. INTRODUCTION

Because energy is constantly in short supply and pressure on the environment continues to increase (Shafie *et al.*, 2016), geothermal resources have garnered increasing worldwide attention as a type of renewable energy (Demirbas, 2002). The efficient, stable, safe and clean energy can be used for generating electricity (Rasit, 2016), space heating, heat pumps, greenhouse heating, and industrial usage (Demirbas, 2016). Geothermal resources can be divided into hydrothermal and pressure categories, with associated geothermal resources of oil and gas according to the type of occurrence or into high-temperature (greater than 150°C), medium temperature (90–150°C), and low temperature (25–90°C) geothermal resources (Lin *et al.*, 2013).

A hydrothermal-type geothermal resource refers to geothermal energy with high-temperature fluid hosted in high-permeability pores or fractures (Wang *et al.*, 2012). A different calculation method is used to evaluate each type of geothermal resource (Shah and Bushnaq, 2017). For the aforementioned three temperature types of geothermal resources, evaluation is done mostly with the surface heat flow, volumetric, hydrothermal equilibrium, and analogy methods. The surface heat flow method is also known as the natural heat quantity calculation method and includes the measurement and calculation of geothermal energy in its natural state using the geothermal fluid convection in the earth's surface (Khan *et al.*, 2017). This evaluation method is the preliminary one for geothermal resources because it is simple, feasible, and low-cost. The water thermal equilibrium method is suitable mostly for mountain fissure water and mountain basins. The analogy method utilizes the geothermal resources in known geothermal fields to calculate the geothermal-geological and hydro-geological conditions in unknown areas of the geothermal resources field and is also a method of preliminary estimation (Mustapha *et al.*, 2017). The volume method is not only applicable to the calculation of non-volcanic geothermal resources (Mendrinos *et al.*, 2008; Ali *et al.*, 2017); it also can be applied to the calculation of geothermal resources in recent volcanic activities.

From the point of occurrence and migration of geothermal fluid medium, this common method applies to pore, fracture, karst, and other kinds of thermal storage (Aravena, 2016; Jie and Xiaojun, 2017). Once mass flux and its thermal properties are determined, the thermodynamic and economic constraints for conversion to electric power can be calculated (DiPippo, 2012; Zarrouk, 2014).The volume method, therefore, has a wide scope of applicability and provides reliable results.

The reserves of fossil fuels are limited and their large-scale use is associated with environmental deterioration (Manzano *et al.*, 2010). Renewable energy sources have significantly become a reality as an alternative to the use of fossil resources and for the reduction of associated adverse effects. Geothermal resources of high-enthalpy (temperatures higher than 150°C) have been widely exploited to generate electricity (Rubio *et al.*, 2016). It is well known that burning of fossil fuels (Coal, oil, and natural gas) generates pollutant harmful gases (SO_2, CO, NO_X and CO_2) that cause environmental pollution problems (Bose *et al.*, 2013; Oktay, 2007).

However, development and utilization of geothermal resources will not cause these environmental

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pollution problems (Abdullah and Rashid, 2017). Therefore, this paper used the volume method to evaluate the potential, economic and environmental benefits of hydrothermal-type, high-temperature geothermal resources in China.

2. FORMATION AND DISTRIBUTION OF HIGH-TEMPERATURE GEOTHERMAL ZONES

Geothermal resources are widely distributed in China with many different kinds and abundant stocks. Geothermal resources have obvious regularity and zonal distribution, but under the control of factors such as formation lithology, structure, magmatic activity, and hydrogeological conditions, the overall distribution is not uniform. The high-temperature geothermal resources of mainland China are distributed mostly in southern Tibet, western Yunnan, and western Sichuan, with more than 200 high-temperature geothermal systems located in these areas.

China's high-temperature hydrothermal convection systems are distributed mainly in the southwest. In Tibet, continent-continent collision has occurred with the continental crust remitting, whereas in Tengchong, the magma is neutral. In the Minyue area, large tectonic magma intrusion is absent; however, some deep-cycle, high-temperature heat source systems lacking magma may be present in the fracture zone.

3. EVALUATION OF RESOURCE POTENTIAL

3.1 Evaluation Theory of High-Temperature Geothermal Potential

The high-temperature geothermal resources evaluation method first assesses whether a geothermal area is in a high-temperature geothermal system, with drilling and logging as the best ways to do so, but it is too expensive to do it in the large area. The volume method proposed by White in 1975 is widely used (White, 1975), using a general heat reservoir thickness of 1 km. The method starts measurement from the spring in the direction of the tectonic line, stretches 0.75 km in the direction of the vertical construction line on each side, and then stretches 0.5 km from the spring perpendicular to the construction line on each side, resulting in a heat storage area of 1.5 km2. According to these parameters and based on the resource evaluation method, the heat thermal energy storage can be calculated first, and then the wellhead heat energy can be calculated. The third step is to calculate the well useful work, and, finally, the power generation potential of the geothermal field is calculated.

3.2 Calculation Method and Parameter Selection

In terms of calculating parameters of the resource, the more reliable ones are the rock and water volume specific heat (2.7 J/g ℃) and the geothermal environmental temperature in the field.

(1) Calculate the heat thermal energy storage, i.e. the amount of geothermal resources. The heat thermal energy storage, Wr, can be obtained using the volume method:

$$Wr = V\rho\,(T - T0)$$

where Wr is the heat thermal energy storage (J); V is the thermal storage volume (m3); ρ is the rock and water volume specific heat; generally taking 2700 j/m3/°C; T is the thermal storage temperature (°C); and T0 is the local annual mean temperature (°C).

(2) Calculate the well head heat, Qwh, that can be extracted from the drill hole portion of the heat energy, by multiplying Wr by the thermal storage heat recovery rate, Rg (typically 0.25), shown as follows:

$$Qwh = Wr \times Rg$$

(3) Calculate the useful work, Wa. For the geothermal fluid to generate power, first the thermal energy needs to be converted into kinetic energy and then the kinetic energy into electricity. According to the first law of thermodynamics, i.e., the law of conservation of energy, useful work can be obtained from the equation below:

$$Wa = (H - H0) - T0\,(S - S0)$$

where Wa is useful work (J); H and H0, respectively, represent the emissions of fluid in the wellhead and tail water discharge enthalpy, leading to (H - H0) as the total heat; S and S0, respectively, represent the fluid in the wellhead and tail water discharge when the entropy, and T0 (S – S0) is the thermal energy failed to be converted in the reversible process.

However, in practice it is not this complicated. As long as the temperature of the heat storage is known, Wa/Wr (Figure 1) can be found, and Wa can be obtained by multiplying the heat thermal energy storage by this ratio (Liao, 2015).

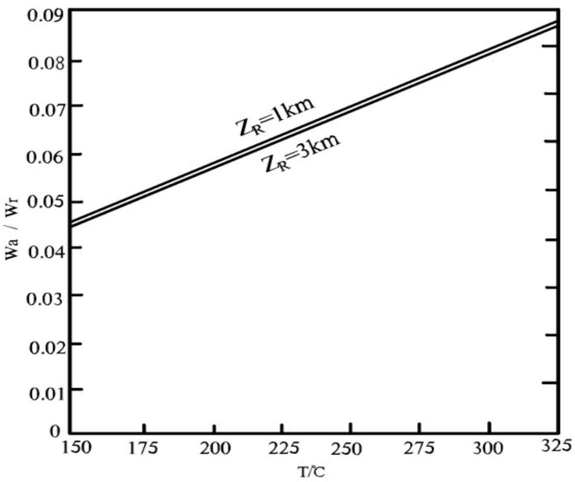

Fig. 1. The ratio of the useful work (Wa) and the heat thermal energy storage(Wr), Liao, 1999.

4) To calculate power generation potential:

$$E = Wa \times B$$

Where E is the electricity generating potential (J) and B is the working efficiency of kinetic energy conversion into electricity.

For working fluids with different temperatures and circulation systems of different types, the working efficiency contains much variation. B is generally 0.1–0.3 for single flash, 0.3–0.4 for binary, 0.4 for secondary flash, 0.5 for full flow, and 0.6 for steam systems.

The electricity generation power conversion over 30 years is calculated as follows:

$$P = E / 946080000 /106$$

where P is the electricity generation power (MW) over 30 years: 946080000 = 30 y × 365 d/y × 24 h/d × 3600 s/h.

3.3 Calculation Results

According to the geothermal resource investigation and evaluation results from 31 provinces, cities, and districts throughout the country, Tibet, Sichuan, Yunnan, Jiangxi, Xinjiang, Jilin, Guangdong, Guangxi, Fujian, and Shanxi, have geothermal resources with temperatures greater than 150°C. The high-temperature geothermal energy (including sedimentary basin type and uplift mountain type) suitable for power generation in China is 100-200 billion t of standard coal. The resource potential is 200-400 million t/y, with a power generation potential of 6–9 million kw/30 y

4. PREDICTED ECONOMIC AND ENVIRONMENTAL BENEFITS

First, according to the availability of high-temperature geothermal resources, take the median (300 million t/y) when calculating the economic benefits. Second, according to the conversion coefficient of raw coal in General Principles of Comprehensive Energy Consumption Calculation (GB/T2589-2008, China), and taking into account factors such as coal combustion and thermal efficiency, the coal savings of high-temperature geothermal resource is 500 million t with a coefficient of 1.6667. Moreover, the economic benefits of geothermal resources were evaluated after the energy conversion to standard coal was calculated at 120 USD/t, and the hydrothermal-type high-temperature geothermal resource potential can produce the value of 60 billion USD/y (Table. 1).

According to the geothermal resource investigation and evaluation results from 31 provinces (cities, districts) all over the country, with reference to the ratio coefficient from Geothermal Resources Geological Exploration Rules (GB/T11615-2010, China), combined with the coal saving amount per year, the environmental benefits brought by water heat high-temperature geothermal resources are shown in Table 2.

Table 1. The economic benefits of high-temperature geothermal resource hydrothermal-type.

The resource potential (million t/a)	The coal savings (million t/a)	Geothermal resource value (billion USD/a)
200-400	500	60

Table 2. The environmental benefits of high-temperature geothermal resource (hydrothermal-type.

The coal savings		SO2	NOX	CO2	Suspension dust	Cinder	Environment administration fee
500 (million t/a)	Ratio	0.017	0.006	2.386	0.008	0.1	--
	Result	8.5 (million t/a)	3 (million t/a)	1.19 (billion t/a)	4 (million t/a)	50 (million t/a)	22 (billion USD/a)

5. DISCUSSION AND CONCLUSIONS

5.1 Rich Geothermal Stocks

It is estimated that heat stored in the earth's interior is approximately 170 million times the world's coal reserves, among which the available amount is equivalent to 4.948 quadrillion tons of standard coal. Assuming that the world continues to consume 19 billion tons of standard coal per year, geothermal resources can meet humankind's energy needs for hundreds of thousands of years adopts three plans as follow: dedicated access, T access and grid connected of consumer side.

China is rich in geothermal resources with high development potential. Tibetan geothermal reserves rank first in the nation. China's largest geothermal power station in Tibet - Yambajan Geothermal Power Plant is a typical Chinese geothermal power generator. The accumulative electricity generation in Tibet's Yambajan Geothermal Power Plant in March 2011 was 2.576 billion kWh with a CO_2 emission reduction of 280 t compared to coal-fired power plants.

The geothermal resources currently used are less than 0.1% of the available stocks. The geothermal resources potential are fairly large.

5.2 Advantages of Using Geothermal Resources

The most prominent advantage of geothermal resource usage is that its utilization coefficient is the highest of all renewable energy types. According to the United Nations World Energy Assessment report (WEA), data in 2007 showed that wind power generated 3.3% of the world's renewable energy electricity (including water and electricity), and its annual utilization coefficient was

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21%; solar power generation accounted for 2.2% with a utilization coefficient of 14%; geothermal power generation accounted for 1.8%, but its utilization coefficient was 72%.

Simply speaking, of the 8,760 hours in one year, the world's average geothermal energy can run from 6,310 to 6,660 hours. In fact, many advanced geothermal power generation units have had utilization coefficients as high as 85 to 95%. In the family of renewable energy types, the utilization coefficient of geothermal energy is 3.6 times that of wind energy and 5.4 times that of solar energy. These differences explain why even though the world wind power facilities installed in 2004 was nearly three times that of geothermal power facilities, the total wind power generated was still less than the total geothermal power generated.

Other advantages of using geothermal resources include security, stability, and immunity to seasonal and diurnal variation, cleanness, low carbon emissions, and renewability

5.3 Cost of Geothermal Power Generation is Acceptable and Decreases as Technology Advances

Power generation costs roughly 1600 USD/kWe when a geothermal facility is installed. The United States spent US$1,300/kWe, which equals approximately 10,000 Yuan, to have the low- temperature Chena Hot Springs Geothermal Facility installed in Alaska.

It is estimated that if one billion Yuan were invested in the development of renewable energy power generation in Tibet, geothermal power could produce 240 million kWh/y, whereas solar power could produce only 18 million kWh/y, a 13-fold difference.

5.4 Geothermal Power has Environmental Advantages

Geothermal energy is an ideal type of clean energy because supplies are abundant and its use does not produce greenhouse gasses. It is not harmful to the environment and reduces emissions by 1.19 billion t CO_2/y according to the coal saving amount per year (Table 2).

6. SUGGESTIONS

6.1 Strengthen Resource Exploration

Increasing exploration and evaluation of geothermal resources and finding out more about the Chinese geothermal resource reserve base is very important. Although geothermal resources in China have been through several rounds of evaluation, the reserve base remains unclear, especially in regards to the large oil and gas geothermal resources in the sedimentary basin, which have not had much evaluation. Exploration and evaluation lag behind the development and utilization, which directly affects development of the geothermal industry.

Technology to explore mining sites accurately as well as to predict where geothermal reserves are located needs to be further developed. Because drilling is very costly, it is very important to find the right mining site to invest in geothermal project construction. In the geothermal industry, people introduce equipment for conventional energy sources, such as oil and natural gas, to explore the mining sites for geothermal energy supplies accurately.

6.2 Promote Technological Progress

(1) Drilling technology

The conventional drilling methods must be improved gradually, such as the use of stronger bits, novel methods of casing, high-temperature cementing technology, sensor improvement, and utilization of downhole instruments that work under high-temperature conditions of electronic devices.

(2) Power conversion technology

Improvements are needed in the heat transfer performance of low-temperature fluids. In addition, modifying power plant design is required, so that a high reservoir temperature of the supercritical water can be withstood, allowing the heat storage performance and thermal substation conversion efficiency to increase by an order of magnitude or more.

(3) Injection technology and anticorrosion

Using the geothermal recharge well to inject used geothermal fluid or other water sources, back into the hot reservoir section, would be an improvement. Injection is not only a good way to solve the problem of geothermal waste water, but also can improve or restore thermal storage capacity of heat, keep the hot reservoir fluid pressure, and maintain the mining conditions of the geothermal field. However, the technical requirements for injection are complex, and the cost is high because promotion of its utilization on a large scale has been unsuccessful. If the problems associated with injection cannot be resolved effectively, geothermal power plant projects will be hindered. Therefore, solving the geothermal injection issue is vital.

Geothermal power generation or direct use often will meet with the well tube, deep well pump and pump pipe, wellhead equipment, piping, heat exchanger, and special equipment, causing corrosion, which leads a large reduction in the service life of the system equipment, and thus an increase in the production cost and difficulty with normal operation. Geothermal water scaling is a ubiquitous phenomenon in the operation of geothermal systems and is one of the major issues impacting the normal and efficient operation of the geothermal system. Therefore, developing anticorrosive and antiscale technologies, such as chemical antiscaling, anticorrosion coating, and geothermal water treatment, is an urgent matter.

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