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Assessment of Geothermal Resources in China

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ABSTRACT

The geological features of the geothermal resources in China have been analyzed firstly. The geothermal resources were then characterized of different categories such as shallow, sedimentary basins, apophysis mountains, and hot dry rocks (potentially for enhanced geothermal systems, EGS). The potential geothermal resources of different types in China have been assessed on the basis of the geological analysis by using different methods and models. The results of the geothermal resources in China are summarized. The key cities of China have shallow geothermal resources of about 2.78×10^{20}J,of which approximately 2.89×10^{12}kWh might be utilized annually. The geothermal resource in the main sedimentary basins of China is about 2.5×10^{22}J, and the quantity of allowable exploitation is close to 7.5×10^{21}J. The total heat discharged from the hot spring areas is roughly 1.32×10^{17}J, and the recoverable resource is about 6.6×10^{17}J/year. The geothermal resources in hot dry rocks (or EGS) areas at a depth of 3.0-10.0km in mainland China is around 2.52×10^{25}J. The geothermal energy is equivalent to5300 times of China's current annual total energy consumption (2010: 95.2×10^{18}J) if only 2% of the EGS resources can be recovered.

1. FEATURES OF GEOTHERMAL RESOURCES IN CHINA

1.1 Category of Geothermal Resources

Geothermal resources can be divided into different types by geothermal reservoir rock types, geological genesis and hydrothermal transmission mode (Chen et al., 1996; Tian et al., 2006). According to the rock types of geothermal reservoirs, geothermal resources can be divided into porous type, fracture type, and karst fracture geothermal resources. According to geological genesis, they can be categorized as sedimentary basins and apophysis mountains geothermal resources. They can also be divided into conductive and convective geothermal resources according to hydrothermal transmission mode. Most frequently, geothermal resources are classified by the temperature of resources: high-temperature (the temperature is ≥150℃), intermediate-temperature (the temperature is <150℃ and ≥90℃) and low-temperature geothermal resources (the temperature is <90℃). Furthermore, geothermal resources of apophysis mountains type can be divided into volcano type, non-volcano type and deep-recycle type according to heat source, structure and other comprehensive conditions. And sedimentary basin geothermal resources can be divided into graben basins and down-warped basins according to tectonic property of the basins. The geothermal resource types ranked by temperature in the main sedimentary basins of China are shown in Figure 1.

Figure 1 Simplified map of Geothermal Resources in China's mainland (modified from Chen et al., 1996). The abbreviations are: SL, Songliao Basin; NC, North China Basin; NJ, North Jiangsu Basin; JH, Jianghan Basin; ED, Erdos Basin; SC, Sichuan Basin; YM, Yumen Basin; TH, Tuha Basin; JG, Jungar Basin; TR, Tarim Basin and QD, Qaidam Basin.

Several categories of geothermal resources were evaluated in the 1970's by the U.S. Geological Survey (White and Williams, 1975; Muffler, 1979). Tester et al. (2006) considered all the aspects of EGS development from resource base to the environmental effects. Based on the analysis of current classification approaches to geothermal resource, we divided the geothermal resources of China into four major categories with the consideration of geological features, hydrothermal transmission mode, and resource temperature, etc. These include sedimentary basins geothermal resources, apophysis mountains geothermal resources, shallow geothermal resources and hot dry rocks resources.

1.2 Features of Geothermal Resources

Geothermal resources are extensively distributed in China with diverse categories and rich capacity. However, they are not distributed evenly due to the effect of tectonic, magmatic activity, stratum lithology and hydrogeology conditions (Chen et al., 1994). Geothermal resources in China include high-temperature type, but mainly low-temperature and intermediate-temperature geothermal resources. Meanwhile, high-temperature geothermal resources are mainly distributed in southern Tibet, western Yunnan, western Sichuan and Taiwan provinces, and over 200 high-temperature geothermal systems have been found. Intermediate and low-temperature geothermal resources are mainly distributed in the fault zone of large sedimentary basins and mountains. Those resources distributed in the fault zone of mountains are generally smaller. While those distributed in the basins, especially in large sedimentary basins, are generally characteristic of good reservoir conditions, multiple and thick reservoirs, and extensive distributions. The temperature rises with the depth and the geothermal resources are great, which makes these areas become the greatest potential targets for exploring geothermal resources.

The geothermal reservoir temperature at a specific depth can be calculated according to terrestrial heat flow, geothermal gradient and surface temperature. Generally, the stronger the tectonic activity or the smaller the formation-heat event is, the higher the heat flow values are. The heat flow values of the ancient blocks with stable geological structures are comparatively lower. Based on the heat flow values collected all around the country (810 in total), the average value of national heat flow in China was about 62.7 mW/m^2.

The values of the terrestrial heat flow in China are distributed unevenly. Overall, southern Tibet, the Western Taiwan Basin, Yongtai and Nanjing Basin in Xiamen had the highest values. The average value was 100~150mW/m^2. Locally, the value was up to 304mW/m^2. The second important areas with high heat flow were Yanghu Basin and Qianghu Basin in northern Tibet, Ordos Basin, Sichuan Basin, coastal basin in southern China, south part of northern China, northern Songliao Basin, northern Suzhou, Bohai Bay Basin and Haier Basin. The average value was 55~80mW/m^2. The third important areas with relatively high heat flow were Tarim Basin, Junggar Basin in Xinjiang, northern Sichuan Basin, northern Songliao Basin and Three-River Basin. These are cold basins with an average value of 30~50mW/m^2.

The geothermal gradient of the sedimentary basins in China was in the range of 1.5~4.0℃/m with an average value of 3.2℃/m, which is controlled by thermal alteration of the centrosphere and the heat conductivity of the stratum medium. Compared with terrestrial heat flow, geothermal gradient was influenced by regional geotecture and correlated closely with the stratum lithology and structure, which formed the different trends of geothermal gradient and terrestrial heat flow. The maximum value of geothermal gradient in sedimentary basins was mainly distributed in Yunnan Tengchong, Beibu Gulf Basin, Xiamen and Shantou, most areas of North China Plain (the south part), the extreme south part of the Bohai Sea and Tianjin, Hailar Basin, west of Qaidam Basin and Songliao Basin. The value was 3.0~4.0℃/m, constituting about 1/10 of the total area of all sedimentary basins in the whole country. The geothermal gradientsin most of the sedimentary basins ranged from 2.0to 3.0℃/m, the rest was below 2.0℃/m. These areas are mainly distributed in Tarim Basin, parts of Junggar Basin and the northwest part of Sichuan Basin (Chen et al., 1988; Qiu et al., 2004).

2. ASSESSMENT METHOD OF GEOTHERMAL RESOURCES

2.1 Assessment Method of Shallow Geothermal Resources

Shallow earth-temperature potential resources can be assessed by calculating calorific capacity with the volumetric method listed in the standard: *Survey and Assessment Code for Shallow Geothermal Resources* (DZ/T 0225-2009, China standard).

2.1.1 Calculation of specific heat capacity

1) In the two-phase zone saturated with both air and water, the specific heat capacity can be calculated by the following formulas:

$$Q_R = Q_S + Q_W + Q_A \qquad (1)$$

$$Q_S = \rho_S C_S (1-\phi) M d_1 \qquad (2)$$

$$Q_W = \rho_W C_W \omega M d_1 \qquad (3)$$

$$Q_A = \rho_A C_A (\phi - \omega) M d_1 \qquad (4)$$

where: Q_R is heat capacity of shallow geothermal resources, kJ/℃; Q_S heat capacity of soil at shallow depth, kJ/℃; Q_W heat capacity of water in the soil at shallow depth, kJ/℃; Q_A thermal capacity of air in the soil at shallow depth, kJ/℃; ρ_S density of the soil, kg/m^3; C_S specific heat capacity of the skeleton, kJ/(kg·℃); porosity of the soil; M area, m^2; $d_1$thicknessof the two-phase zone, m; ρ_w water density, kg/m^3; C_W specific heat of water, kJ/(kg·℃); ω water content of the soil; ρ_A air density, kg/m^3; C_A specific heat of air, kJ/(kg·℃).

2) In the water zone, the specific heat capacity can be calculated by the following formulas:

$$Q_R = Q_S + Q_W \qquad (5)$$

$$Q_W = \rho_W C_W \omega M d_2 \qquad (6)$$

$$Q_S = \rho_S C_S (1 - \phi) M d_2 \qquad (7)$$

where: d_2 is the lower-limit depth to the water level.

2.1.2 Calculation of resource capacity

Capacity of the shallow geothermal resource is the product of the specific thermal capacity of the geothermal reservoir and the available temperature difference in the assessed area. The recoverable resource should consider the area coefficient of urban building, recoverable coefficient of the shallow geothermal energy and the utilization coefficient. The formula is expressed as follow:

$$Q = Q_R \times \Delta T \times \alpha \times \beta \times \gamma \qquad (8)$$

where: Q is the total recoverable geothermal resource at shallow depth, kWh/a; Q_R the terrestrial heat capacity at shallow depth, kJ/℃; ΔT the available temperature difference, ℃; α the area coefficient of urban building; β the recoverable coefficient of the geothermal energy at shallow depth; γ the utilization coefficient of the geothermal energy at shallow depth.

2.2 Assessment Method of Convective Geothermal Resources

The amount of convective geothermal resources of apophysis mountains at the hot-spring areas can be calculated by the heat release method reported in *Assessment Method for Geothermal Resources* (DZ 40-85, China Standard). We mainly calculate the heat released from the hot springs all over the country.

$$Q = \alpha \times q_V \times c \times \rho \times (t_1 - t_0) \qquad (9)$$

Where $c\times\rho\approx1$, then

$$Q = \alpha \times q_V \times (t_1 - t_0) \qquad (10)$$

here: Q is resource potential of heat released from the hot springs, k·cal/s; α utilization ratio of hot springs; q_v flow rate of hot springs, L/s; c specific heat of hot-spring water, k·cal/kg·℃; ρ density of hot-spring water, kg/L; $t_1$temperature of hot-spring water, ℃ ; $t_0$temperature of the constant temperature layer in the non-thermal abnormal region, ℃.

2.2.1 Assessment Method of Conductive Geothermal Resources

The volumetric method was mainly used in this study to assess the conductive geothermal resources. There are two ways to apply for the volumetric method. The first method is expressed by the following formula:

$$Q = A \cdot D(T - T_{ref})(\rho_w \cdot C_w + \rho_s \cdot C_s) \qquad (11)$$

where: Q is geothermal resources; A calculated area; D average thickness of the geothermal reservoir; T average temperature of the geothermal reservoir; T_{ref} reference temperature. The second assessment method is expressed as follows:

$$Q = V(T - T_{ref})(\rho_w \cdot C_w + \rho_s \cdot C_s) \qquad (12)$$

where: Q is geothermal resources; V volume of buried hill, which is the product of the area and average thickness. Geothermal resources of the carbonate rock at buried hill in North China Plain are calculated by the above method.

2.2.2 Assessment Method of Hot Dry Rock Resources

Resources of hot dry rock resources in mainland China was also calculated by the volumetric method expressed as:

$$Q = \rho C_P V(T - T_0) \qquad (13)$$

where: Q is resources of hot dry rock; ρ density of rock; $C_p$specific heat capacity of rock; V volume of the rock; Trock temperature at thecalculated depth; T_0surface temperature.

The drilling depth at present is often less than 5000m.When the temperature condition at the depth cannot be tested directly, the temperature at the part exceeding the drilling depth can be inferred by indirect methods. Under stable heat flow, temperature of deep part can be calculated by the following formula:

$$T(z) = T_0 + q_0 \sum(Z_i/K_i) - 0.5\left[A_0 Z - \left(A_0 - A^{\prime}\right) Z^2/\left(2Z^{\prime}\right)\right] \times \sum(Z_i/K_i) \qquad (14)$$

where: T_0 refers to surface temperature, q_0 heat flow on the surface, A_0heat generation rate on the surface, Z_i and K_i refer to thickness and thermal conductivity of each layer respectively, A' and Z' are heat generation rate at the bottom and total thickness at the calculated layer respectively.

In general circumstance, the following formula is used for simplification:

$$T(z) = T_0 + (q_0 z)/K - (Az^2)/2K \qquad (15)$$

In the deep crust and the upper mantle, heat generation rate is often inexponential distribution and decreases with depth:

$$T(z) = T_0 + [(q - AD)/Z]/K + AD^2[1 - exp(-ZD)]/K \qquad (16)$$

or

$$T(z) = T_0 + q_0 Z/K - A'D^2\left(1 - e^{-Z/D}\right)/K \qquad (17)$$

where: $q_0$is heat flow value of the upper surface, K thermal conductivity, Z the depth, and D the thickness of the concentrated layer with radioactive elements.

Based on the heat flow map of China's mainland, which is shown in Figure2, HDR potential resources have been estimated.

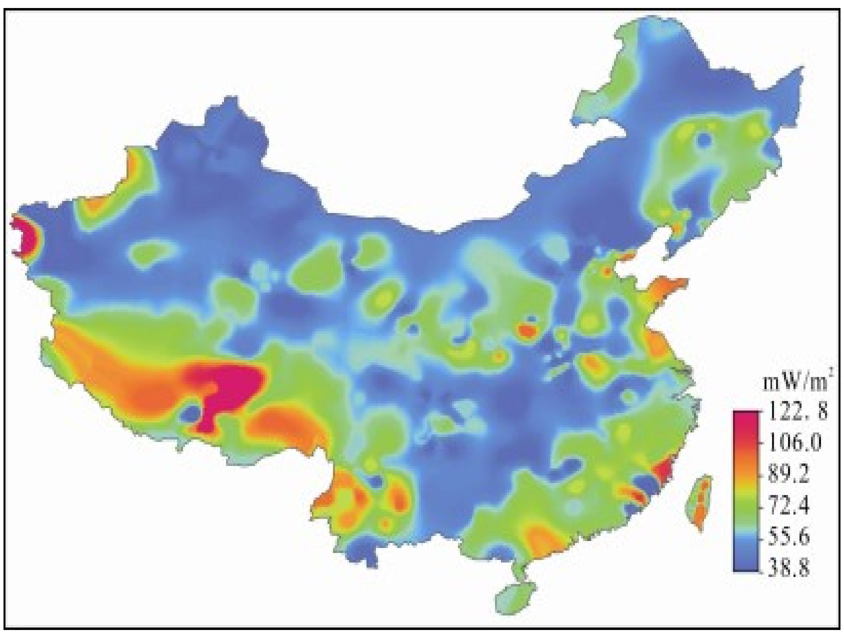

Figure 2 Heat flow map of China's mainland (5′×5′) (modified from Lin et al., 2012)

The temperature distribution maps at different depth (from 3.5 km to 9.5 km) were obtained using the above formulas (14-17). The results are illustrated in Figure3.

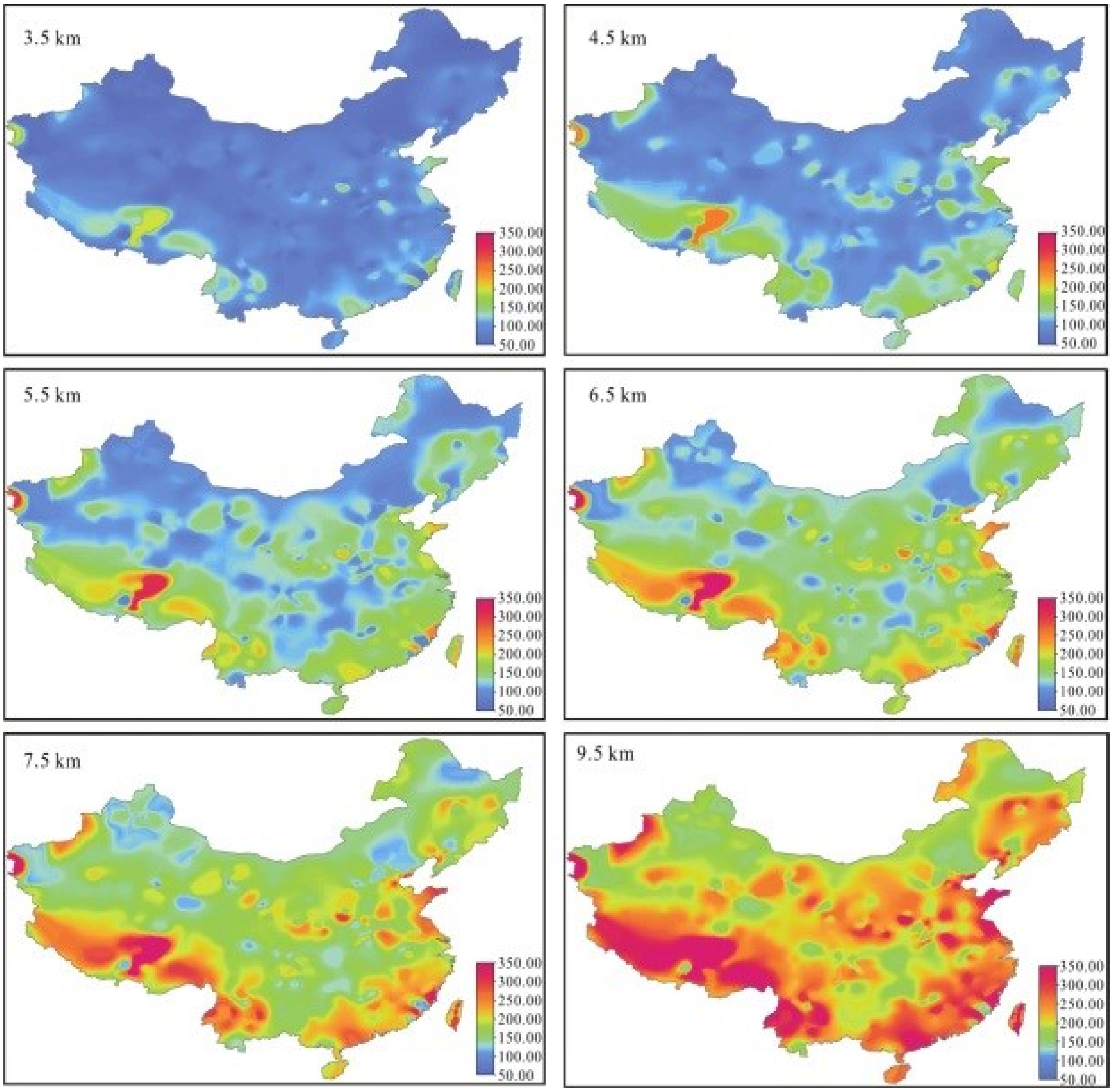

Figure 3 Average temperature at different depths from 3.5 km to 9.5 km (modified from Lin et al., 2012)

3. ASSESSMENT RESULTS OF GEOTHERMAL RESOURCES

3.1 Shallow Geothermal Resources in Key Cities

The shallow geothermal resources in 287 key cities in China were estimated according to geological data of shallow depth within 200m offered by Geological Survey Institutions of all the provinces. The assessment results show that the total shallow geothermal resources are 7.71×10^{13}kWh/a, which is equivalent to9.486 billion tons of standard coal. Given that the area coefficient of urban building is 0.25, the recoverable coefficient of shallow geothermal resources is assumed to be 0.3 and the utilization ratio is 0.5, then the total recoverable shallow geothermal resources are 2.89×10^{12}kWh (equivalent to 356 million tons of standard coal). Shallow geothermal resources of 31 provinces (cities and districts) were also estimated and the results are listed in Table 1.

3.2 Assessment Result of Resources of the Sedimentary Basins Geothermal Resources

Geothermal resources of the major plains (basins) are 24964.4×10^{18}J, which is equivalent to 8531.9×10^{8}T standard coal. The results are shown in Table 2.

Table 1 The benefit analysis and assessment of shallow geothermal resources of China

Serial No.	Province (city, district)	Planning area of central area km^2	Total resource capacity		Available resource capacity and benefit		
			kWh	Standard coal 100 million tons	kWh	Standard coal 100 million tons	CER of CO_2
1	Beijing	2580	3.01E+12	3.70	1.13E+11	0.14	0.36
2	Tianjin	1450	1.75E+12	2.15	6.56E+10	0.08	0.21
3	Shanghai	1700	2.30E+12	2.83	8.64E+10	0.11	0.28
4	Chongqing	1000	1.54E+12	1.89	5.79E+10	0.07	0.19
5	Hebei	1820.00	2.32E+12	2.85	8.70E+10	0.11	0.28
6	Shanxi	1208.31	1.67E+12	2.05	6.27E+10	0.08	0.20
7	Inner Mongolia	1586.26	1.80E+12	2.21	6.77E+10	0.08	0.22
8	Liaoning	3566.83	3.30E+12	4.06	1.24E+11	0.15	0.40
9	Jilin	2070.00	1.84E+12	2.26	6.91E+10	0.09	0.22
10	Heilongjiang	3318.00	3.31E+12	4.07	1.24E+11	0.15	0.40
11	Jiangsu	4080.00	7.13E+12	8.77	2.68E+11	0.33	0.86
12	Zhejiang	2739.00	4.57E+12	5.62	1.71E+11	0.21	0.55
13	Anhui	2560.06	3.83E+12	4.71	1.44E+11	0.18	0.46
14	Fujian	2450.00	3.49E+12	4.29	1.31E+11	0.16	0.42
15	Xinjiang	450.00	4.86E+11	0.60	1.82E+10	0.02	0.06
16	Tibet	295	3.30E+11	0.41	1.24E+10	0.02	0.04
17	Qinghai	128.4	1.60E+11	0.20	6.00E+09	0.01	0.02
18	Ningxia	810.00	9.74E+11	1.20	3.65E+10	0.04	0.12
19	Gansu	1266.21	1.21E+12	1.49	4.55E+10	0.06	0.15
20	Shaanxi	2087.00	2.24E+12	2.76	8.42E+10	0.10	0.27
21	Yunnan	730.00	9.72E+11	1.20	3.65E+10	0.04	0.12
22	Guizhou	482.00	6.87E+11	0.85	2.58E+10	0.03	0.08
23	Sichuan	2080.00	3.10E+12	3.81	1.16E+11	0.14	0.37
24	Hainan	800.00	9.78E+11	1.20	3.67E+10	0.05	0.12
25	Guangxi	1220.00	1.58E+12	1.94	5.91E+10	0.07	0.19
26	Guangdong	5230.00	8.11E+12	9.98	3.04E+11	0.37	0.98
27	Hunan	1710.00	2.21E+12	2.72	8.29E+10	0.10	0.27
28	Hubei	2685.00	3.92E+12	4.82	1.47E+11	0.18	0.47
29	Henan	2668.00	3.45E+12	4.24	1.29E+11	0.16	0.42
30	Shandong	2964.93	3.47E+12	4.27	1.30E+11	0.16	0.42
31	Jiangxi	1215.50	1.36E+12	1.67	5.09E+10	0.06	0.16
Total up		58950.50	7.71E+13	94.86	2.89E+12	3.56	9.32

3.3 Assessment Results of the Geothermal Resources of Hot Springs

According to the calculation and statistics, the total heat released from hot springs in China is 31.627848 trillion kilocalorie/year, i.e., 1.32×10^{17}J, which is equivalent to the heat generated from burning 4.5183 million tons of standard coal. Given that the recoverable coefficient is 5.0, then the recoverable geothermal resources of convective apophysis mountains typeis6.6×10^{17}J/year, which is equivalent to 22.591 million tons of standard coal. The heat released from hot springs in all provinces (cities) was calculated and the results are illustrated in Table 3 (Huang et al., 1993).

Table 2 The geothermal resources assessment of main plains (basins) of China

Plain (basin)	Area (km^2)	Calculation of geothermal reservoir lithology	Thermal energy($\times 10^{18}$J)	Amount to standard coal ($\times 10^8$T)
North China Plain	90000	Minghuazhen Formation, Guantao Formation, carbonatite in buried hill	5420.5	1852.5
Huaihe River Basin	68050	Recent system	1984.7	678.3
North Suzhou Basin	31750	Recent system	495.0	169.2
Downstream Liao River Basin	3385	Recent system	31.9	10.9
Weihe River-Yuncheng Basin	24625	Recent system, Quaternary system	3652.1	1248.2
Songliao Basin	144400	Middle Cretaceous system, Plioceneseries	992.4	339.2
Erdos Basin	159600	Latter Cretaceous system, Jurassic system, Triassic system, Dyas	2548.1	870.8
Sichuan Basin	200000	Jurassic system, Triassic system, Dyas	7783.8	2660.2
Yinchuan Plain	2515	Tertiary system, Ordovician system	409.8	140.0
Xining Basin	834	The 3rd system	238.7	81.6
Jianghan Basin	28000	Recent system	241.5	82.5
Hetao Plain	28000	Recent system	1165.9	398.5
Total	781159		24964.4	8531.9

Table 3 The geothermal resources of hot springs in China

Province	Heat release (100 millions of kilocalorie/ year)	Amount to standard coal (10000 tons/ year)	Spring number
Beijing	153.30	0.22	3
Hebei	1338.77	1.91	25
Shanxi	12293.68	17.56	7
Inner Mongolia	1022.07	1.46	4
Liaoning	2427.19	3.47	36
Jilin	1681.91	2.40	5
Shandong	1125.25	1.61	17
Jiangsu	2003.72	2.86	5
Anhui	1488.77	2.13	17
Zhejiang	36.22	0.05	4
Jiangxi	3522.50	5.03	80
Fujian	6988.25	9.98	171
Taiwan	10395.42	14.85	28
Henan	2531.88	3.62	23
Hubei	4633.06	6.62	49
Hunan	5584.37	7.98	108
Guangdong	12314.19	17.59	302
Hainan	1488.19	2.13	33
Guangxi	1406.47	2.01	49
Shaanxi	5600.27	8.00	14
Ningxia	133.69	0.19	2
Gansu	366.28	0.52	8
Qinghai	5511.37	7.87	43
Xinjiang	2415.83	3.45	54
Sichuan	22840.42	32.63	241
Chongqing	3322.70	4.75	43
Guizhou	3554.44	5.08	63
Yunnan	88356.30	126.22	820
Tibet	111741.94	159.63	308
Total	316278.48	451.83	2562

3.4 Assessment Results of Geothermal Resources of Hot Dry Rock Resources

The geothermal resources of hot dry rock at the depth of 3.0-10.0km in mainland China were calculated and the total value was up to 2.52×10^{25}J (equivalent to8.56×10^{5} billion tons of standard coal),which is 2.6×10^{5} times of annually total energy consumption of China at present (total energy consumption in China in 2010 was about 3.25 billion tons of standard coal).According to Tester, et al. (2002), the result of America was about 1.67×10^{25}J, excluding Yellowstone National Park.

Table4 shows the geothermal resources of hot dry rock at different depth. Figure5 plots the total geothermal energy of hot dry rock in mainland China. The geothermal energy is equivalent to 5300 times of China's current annual total energy consumption if only 2% of the HDR resources can be recovered.

Table 4 Assessment of the hot dry rock resources in the depth of 3.0-10.0km in China's mainland

Sequence	Calculation of position depth (km)	Thermal energy （$\times10^{25}$J）	Convert to standard coal （$\times10^{5}$ 100 million tons）
1	3.0-4.0	0.19	6.5
2	4.0-5.0	0.25	8.4
3	5.0-6.0	0.30	10.3
4	6.0-7.0	0.36	12.2
5	7.0-8.0	0.42	14.1
6	8.0-9.0	0.47	16.1
7	9.0-10.0	0.53	18.0
3.0-10.0 km		2.52	85.6

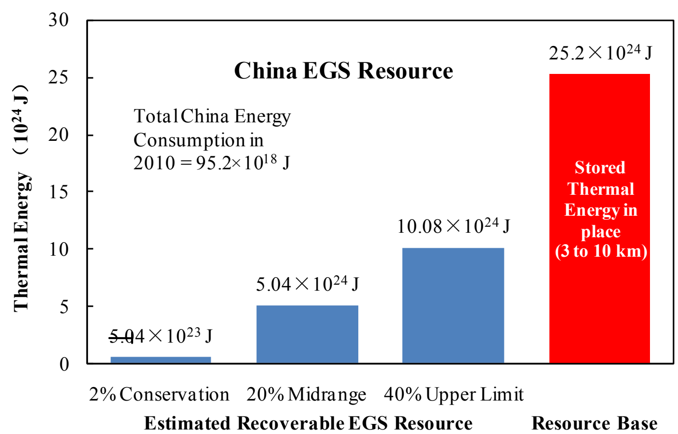

Figure 5 Estimated total geothermal resources and recoverable resources in China's mainland

Figures6 and 7 show the resources of hot dry rock and its distribution area respectively within a certain temperature range at different depth in Mainland China. It can be seen that there are tremendous resources of hot dry rock between 3.5-7.5km and 150-250℃, and the amount is about 6.3×10^{24}J. Even though only 2% is explored, 12.6×10^{22}J heat energy could be obtained, which is equivalent to 1320 times as much as the total energy consumption of China in 2010.

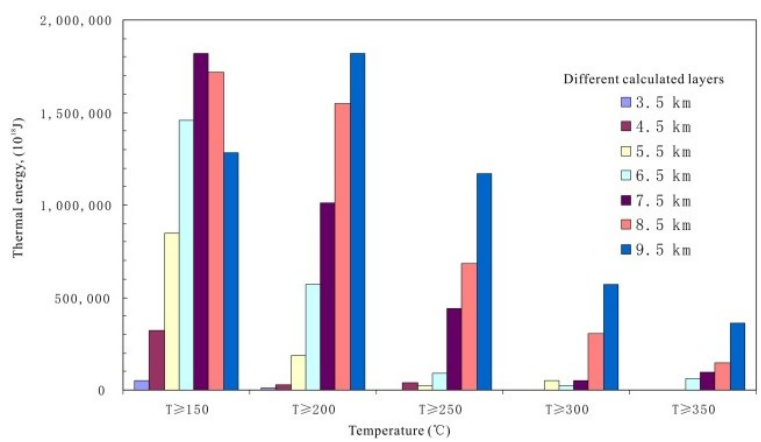

Figure 6 The geothermal resources of HDR at different temperatures and depths

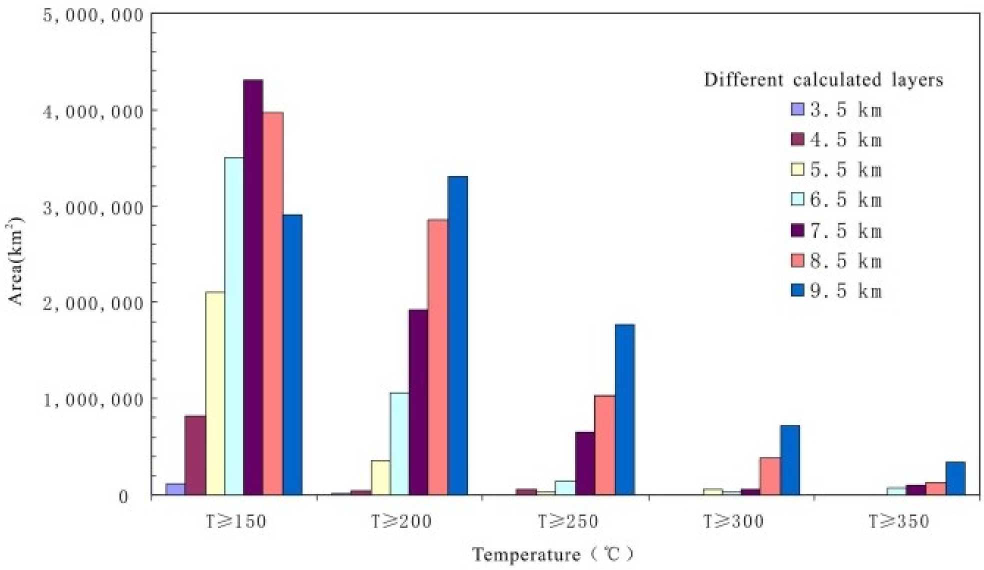

Figure 7 Area of the region of the specified temperature lower limit at different depths

4 CONCLUSION

(1) The capacity of the shallow geothermal resources of key cities in China is 2.78×10^{20}J, which is equivalent to 9.486 billion tons of standard coal. Given that area coefficient of the urban building is 0.25, recoverable coefficient of shallow geothermal resources is 0.3 and the utilization ratio is 0.5, then, the recoverable capacity of shallow geothermal resources per year is 2.89×10^{12}kWh (equivalent to 356 million tons of standard coal).Assuming an energy consumption ratio of 0.3 for exploring and using shallow geothermal resources, the amount of power of 2.02×10^{12}kWh maybe saved each year, which is equivalent to 248 million tons of standard coal, and 652 million tons of CO_2emissionmaybe reduced.

(2) The geothermal resources of sedimentary basin geothermal resources in major plains (basins) in China are 2.5×10^{22}J, which is equivalent to 853.19 billion tons of standard coal. Assuming an actual recoverable coefficient of 0.3, the recoverable resource is about 7.5×10^{21}J, which is equivalent to 255.96 billion tons of standard coal. 1.8×10^{19}J resources can be explored each year, equivalent to 620 million tons of standard coal, and1.4 billion tons of CO_2 emission maybe reduced each year.

(3) Heat release in hot spring area in China is around 1.32×10^{17}J in total, equivalent to 4.52 million tons of standard coal. Given that the actual recoverable coefficient is 0.5, the recoverable geothermal resources in hot-spring areas is about 6.6×10^{17}J/year, which is equivalent to 22.6 million tons of standard coal, and 59.3 million tons of CO_2 emission maybe reduced each year.

(4) Hot dry rock resource in 3.0-10.0km deep of mainland in China is about 2.5×10^{25}J in total, which is equivalent to 860×10^{6} million tons of standard coal. Even though only 2% is explored, the energy is equivalent to 5.3×10^{3} times as much as the total annual energy consumption in China in 2010.

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