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Geothermal Resources Assessment of Middle of Western Sichuan Depression, Sichuan Basin

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ABSTRACT

As the underground mines in new energy and one of oil and gas associated minerals, the evaluation of geothermal resources of SINOPEC Southwest Branch Company is of great significance to the overall exploration and development and utilization of oil and gas associated minerals. SINOPEC Southwest Branch Company have many exploration and mining blocks in Sichuan basin, the research object is exploration block in middle of Western Sichuan Depression. Based on the regional geological setting, structural evolution characteristics, geothermal field and the features of geothermal, the study area is divided into five evaluation units and calculate the geothermal resource of clastic rock thermal reservoir of Triassic Xujiahe Formation-Cretaceous with the thermal energy storage method. The geothermal reservoirs in the study area are Cretaceous, Jurassic Penglaizhen Formation and Shaximiao Formation, Upper Triassic Xujiahe 4 member, Xujiahe 2 member of buried shallower than 4000m in the margin of the basin. The geothermal gradient is 1.9 to 2.4°C/100m, and the geothermal water temperatures range is 27 to 110°C.Based on the parameters of geothermal reservoir area, thickness, heat capacity and density, porosity and temperature, the geothermal resources in the study area is calculated to be 7.97×10^{17}kJ, which is equivalent to 272.18×10^{8}t of standard coal, the exploitable geothermal reserves is 3.98×10^{16}kJ , which is equivalent to 13.61×10^{8}t of standard coal.

1. INTRODUCTION

In recent years, the people pay more and more attention to development and utilization of clean resources, geothermal as a kind of renewable clean energy, especially in focus (Jiyang Wang, 2017; Guiling WANG, 2017, 2020; Wenjing Lin, 2013, Zhang Wei, 2019). Western Sichuan depression of Sichuan basin has rich geothermal resources and multistage application(Chunmei Yu, 2021; Zhang J, 2017; Wenjing Lin, etc., 2013, Gaoqian Ni,2016), the research of hot spring resources is more, characteristics of regional geothermal resources in sedimentary basin research is still rare. SINOPEC Southwest Branch Company have many exploration and mining blocks in Sichuan basin, geothermal resource characteristics of Western Sichuan Depression can be known by a large amount of data accumulated in the process of oil and gas exploration and development.

2. REGIONAL GEOLOGICAL CHARACTERISTICS

2.1 Structure

Sichuan basin is a structural basin with Paleozoic cratonic basin and Mesozonic-Cenozoic foreland basin, multiphase tectonic movement establishes current tectonic pattern. The basement of central Sichuan basin, composed of Archaeozoic basic and ultrabasic rocks with high consolidation. The deposition in Sichuan basin begins from Sinian and end in Eocene. The stage before Middle Triassic was dominated by marine deposition with a thickness of 3-6 km. Due to western China Palaeotethys subducting to east, Songpan-Ganzi arc back basin was formed, and Longmenshan and western Sichuan basin became the shallow marin deposition area in Carnian age. After then, Palaeoqinling and Palaeotethys folded up and Songpan area was compressed and heavy loading resulted in bending the lithosphere and forming the foredeep in the front of Palaeolongmenshan. So Sichuan foreland basin was formed, and the continental basin evolution stage started. In this stage, the thickness of continental deposits would reach 5-8 km, but the existing thickness at present is 2-6 km due to the denudation.

The middle of the western Sichuan depression is located in low steep structural belt of western of Sichuan basin, the main controlling faults are Guankou fault, Dayi-pengxian fault, Xiongpo fault and Longquanshan fault. According to the boundary faults and tectonic characteristics, research area is divided into Xiaoquan-Xinchang-Hexingchang structural belt, Zhixinchang-Longbaoliang tectonic belt, Dayi- Yazihe-Anxian tectonic belt, Chengdu sag and Zitong sag.

2.2 Formation

There are mainly carbonate from Cambrian to Triassic in Sichuan basin. Cambrian, Ordovician, Silurian strata widely distributed in the basin, upper Cambrian and Ordovician in the south of the Chengdu suffers denudation because of the Caledonian movement. The Silurian strata denudation scope is bigger. Devonian and Carboniferous sedimentary just preserved on the edge of the basin. The Permian and Middle-Lower Triassic distribution in the whole basin with a set of shallow marine platform deposits. Large-scale transgression end until the end of the Triassic, Sichuan basin suffered varying degrees of erosion. Upper Triassic is a set of sea and lake transfer and the lake basin. Jurassic to Neogene is continental lake basin with a set of clastic rock.

3 GEOTHERMAL GEOLOGICAL CHARACTERISTICS

3.1 Geothermal reservoir

For large-scale sedimentary basin, Sichuan basin geothermal resources is hydrothermal sedimentary basin conduction type. No geothermal shows in most of the surface except near the fault. Heat source mainly comes from deep in the earth's crust and upper mantle heat conduction, the study area near the Longmenshan fault and Longquanshan fault, heat conduction and convection are advantageous.

Middle of western Sichuan depression geothermal reservoir are Cretaceous, Jurassic Penglaizhen Formation and Shaximiao Formation, Upper Triassic Xujiahe 4 member, Xujiahe 2 member of buried shallower than 4000m.

Cretaceous is mainly constituted by palm red glutenite with mudstone, Cretaceous Jiaguan formation sandstone is aeolian sand with coarse particle, large thickness and good porosity and permeability. Cretaceous usually buried in 300-1050 m. Reservoir porosity is mainly distributed 10-13%, permeability is mainly 5-50 md, formation water salinity is commonly in 7.35-15.57 g/L, and the water temperature is 27-73 °C.

Jurassic Penglaizhen Formation and Shaximiao Formation reservoir are few set of sandstones with in grey, light grey, purple, deposited in channel environment, thickness is in commonly 10 to 50 m. Jurassic Penglaizhen Formation and Shaximiao Formation reservoir buried in the 300-3500 m. Reservoir porosity is 1.57-19.36%, the main distribution of 8-14%, permeability distribution is 0.2-0.8 md, formation water salinity is commonly in 12.71-62.9 g/L, the water temperature is 27-73 °C.

Upper Triassic Xujiahe 4 member sandstone is fine-medium grained lithic sandstone, calcarenaceous sandstone and lithic quartz sandstone, sandstone thickness ranging from 10-100 m. Upper Triassic Xujiahe 4 member buried in 2150-4058 m. Reservoir heterogeneity is obvious, the reservoir porosity of 0.26-13.56%, mainly 4-5%, permeability is mainly 0.2-0.6 md, formation water salinity is commonly in 3.74-122.43 g/L, the water temperature is 56-110 °C.

3.2 Geothermal field

The present geothermal of Sichuan basin is low with the paleo-geothermal was high. The geothermal field and heat flow study of Sichuan basin began in the 1980s. Use of the hundreds of borehole temperature data and a large number of thermal conductivity, heat production rate of thermal physical parameters, there are some knowledge of distribution characteristics of the Sichuan basin geothermal field.

Now Sichuan basin geothermal gradient is 1.77-3.33 °C/100 m, with a mean of 2.28 °C/100 m. On regional distribution, Sichuan basin have obvious features of geothermal gradient. Geothermal gradient of the middle and southwest of Sichuan is higher, between 2.4-3.0 °C/100 m. To the northeast of Sichuan , Geothermal gradient gradually dropped to 2.0 °C/100 m or so, geothermal gradient of the western of Sichuan is 1.5-2.25 °C/100m, geothermal gradient of Guizhou and Chishui area is 2.4-2.7 °C/100 m(FIG. 1).

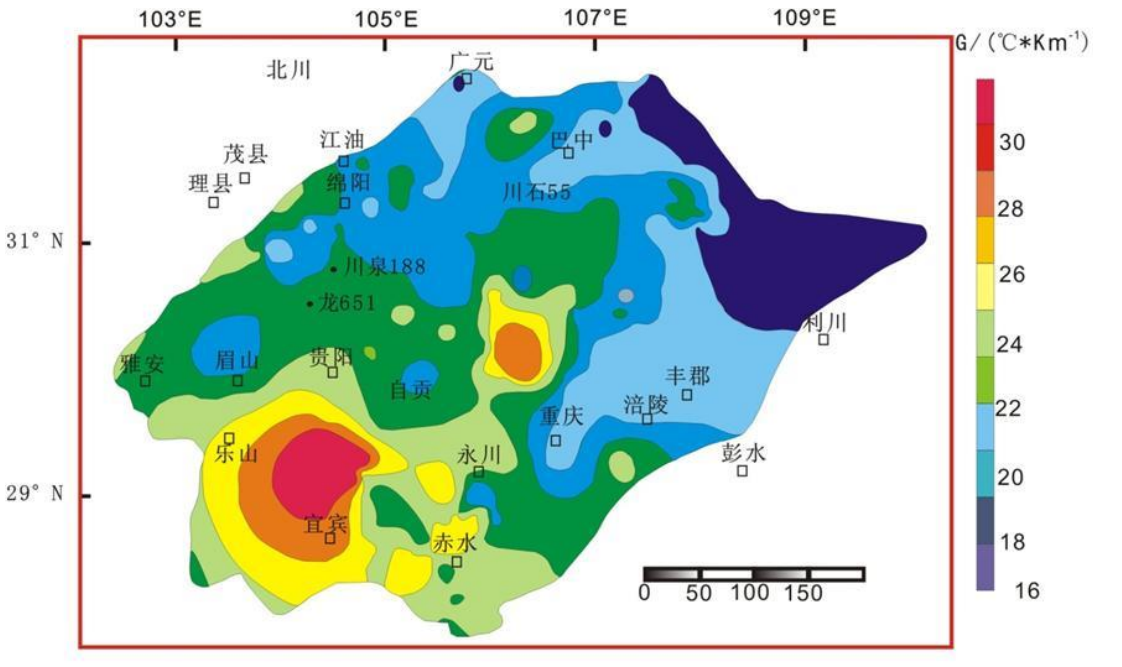

FIG.1 Contour map of geothermal gradient in Sichuan Basin (Based on Xu Ming, 2011)

The terrestrial heat flow of Sichuan Basin ranges from 35.4 to 68.8 mW/m2, with an average value of 53.2 mW/m2, which is similar to that of typical craton basins in the world with low and medium heat flow values. In terms of regional distribution, terrestrial heat flow is obviously controlled by basement structure (FIG. 2). For example, it is 60-70mW/m2 in the uplift area, lower than 60mW/m2 in the depression area, and even lower than 40mW/m2 in the front of Dabashan fold belt in northeast Sichuan Basin.

The current geothermal gradient was calculated by using the measured temperature data of more than 130 data points from more than 50 Wells in western Sichuan, and the geothermal contour map in western Sichuan Basin was compiled (FIG. 3). It can be seen from the figure that the geothermal temperature changes greatly in the region , and the geothermal gradient increases to the south and east on the whole. The geothermal gradient in the Xiaoquan-Xinchang-Hexingchang-Fenggu area ranges from 1.9 to 2.4 °C/100m, and gradually increase from west to east, which may indicate that the large developmental differences of the fault zone between the east and the west, that is, the fault development in Gaomiaozi-Fenggu area is weaker than that in Xiaoquan-Xinchang-Hexingchang area. The geothermal gradient in the Luodai area is the lowest, which is only 0.97°C/100m in Well Long12. The current geothermal gradient in this area is the lowest in the whole region, which may be caused by the rapid drop of the stratum temperature due to the stratum uplift and fault development in Luodai-Longquan area.

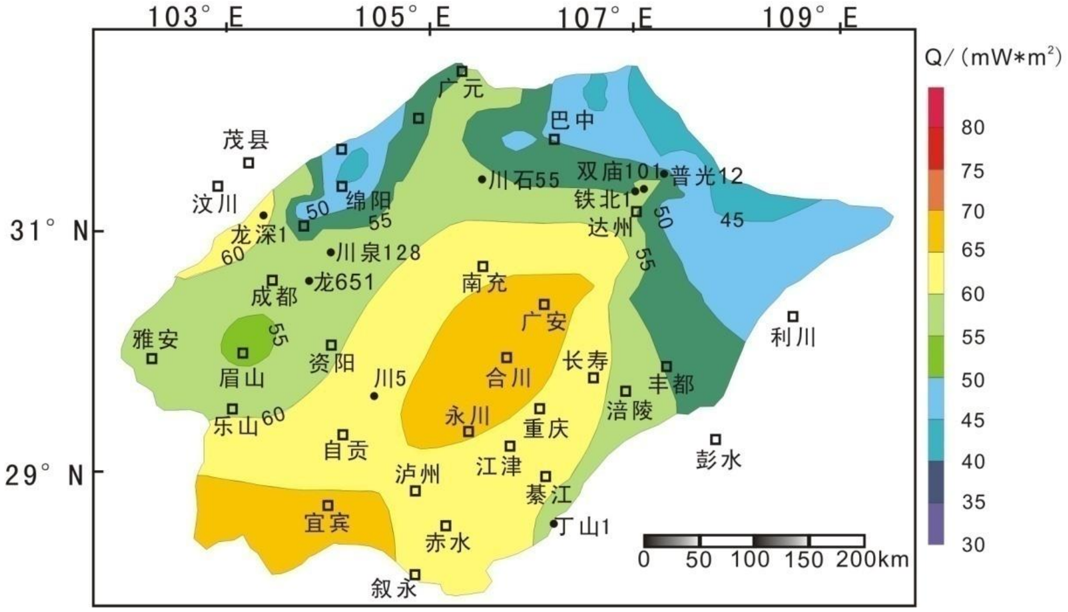

FIG.2 Contour map of terrestrial heat flow in Sichuan Basin(Based on Xu Ming, 2011)

FIG.3 Contour map of geothermal gradient in exploration area of western Sichuan Basin

4 CALCULATION OF GEOTHERMAL RESOURCES

4.1 Calculation parameters

4.1.1 Distribution area of geothermal reservoir

The distribution range of geothermal reservoir is determined based on the comprehensive analysis of geothermal geological survey, geophysical exploration, tectonic geothermal wells and temperature measurement data. The formation water temperature of Cretaceous, Penglaizhen Formation, Shaximiao Formation and Xujiahe formation in the exploration area of western Sichuan Basin ranges from 33 to 101°C, with an average of 64°C. The above value range is the geothermal distribution range in the exploration area of western Sichuan Basin. The structural zone of the western Sichuan Basin depression can be divided into five sub-zone units, and the area of each unit is mainly determined according to the area of mining rights (Table 1).

4.1.2 Geothermal reservoir thickness

The thickness of geothermal reservoir is mainly determined by drilling data combined with geothermal geological conditions. The thickness of geothermal reservoir is the thickness of sandstone reservoir to a large extent. This geothermal resource evaluation will evaluate sandstone larger than 3m. For example, in the NEE Tension Block, the thickness of sandstone of Penglaizhen Formation ranges from 140 to180m, with an average of 160m; the thickness of sandstone of Shaximiao Formation ranges from 40 to 60m, with an average of 50m; and the thickness of sandstone of the fourth member of Xujiahe Formation ranges from 70 to 90m, with an average of 80m. The thickness of sandstone in other strata is shown in Table1.

4.1.3 Specific heat capacity and rock density

The specific heat capacity and density of geothermal reservoir rock were obtained by experiments. However, in the absence of test data in the initial stage of work, the specific heat capacity and density of thermal reservoir rocks in the exploration area of western Sichuan Basin were obtained after comparative analysis according to DZ40-85 "Geothermal Resources Evaluation Method" and combined with actual drilling data and logging data. The density of formation water and specific heat capacity of geothermal reservoir rocks in different strata of each block are listed in Table 1.The density of formation water (ρw) ranges from 1010 to 1900kg/m^3; The specific heat capacity of hot water (Cw) is 4200J/kg·°C.The density of geothermal reservoir rock (ρr) ranges from 2290 to 2560kg/m3.The specific heat capacity of geothermal reservoir rock (Cr) is 894J/kg·°C.

4.1.4 Porosity

The porosity of a pore-geothermal reservoir can be determined either in the laboratory or by logging. A large number of experimental data and mainly measured data have been accumulated for Penglaizhen Formation, Shaximiao Formation and the fourth member of Xujiahe Formation in Chengdu Depression and NEE Tension Block in western Sichuan Basin. For example, the analysis and statistics of 951 samples of sandstone body in Penglaizhen Formation in Chengdu Depression show that the minimum porosity of reservoir is 1.13%, the maximum is 19.39%, and the average is 10.51%. The experimental analysis data of Zitong Depression are lacking, and the porosity is mainly obtained from logging interpretation. Due to the lack of data in Anxian block of piedmont belt, the corresponding porosity is obtained by comparing the porosity of the same stratum in the adjacent block. The porosity of different stratum in each block is shown in Table1.

4.1.5 heat reservoir temperature

The formation water temperature of different stratum in Dayi area can be predicted by the relationship between well depth and temperature in Dayi Well 1. According to this, the formation temperature can reach 104°C when drilling to 4000m of the fourth member of Xujiahe Formation.

When the geothermal reservoir drilled in the working area has little or only shallow geothermal temperature data, the geothermal reservoir temperature should be calculated by using the geothermal temperature gradient in the upper part of the geothermal reservoir according to the geological conditions. Geothermal resources calculated by geothermal reservoir method

4.2 Calculation results

The geothermal resources in the exploration area of western Sichuan Basin were obtained by assigning the parameters of different blocks and different stratum to the calculation formula. The geothermal resources in the exploration area of western Sichuan Basin is 7966709.87×10^{11}KJ, where the geothermal resources of piedmont belt is 1158039.59×10^{11}KJ; the geothermal resources of Chengdu Depression is 4083335.72×10^{11}KJ; the geothermal resources of North-south Tectonic Zone is1600227.45×10^{11}KJ; the geothermal resources of NEE Tension Block is 478022.9×10^{11}KJ; the geothermal resources of Zitong Depression is 647084.21×10^{11}KJ. Geothermal resources in the exploration area of west Sichuan Basin are equivalent to 272.18×10^8t of standard coal, and the recoverable geothermal resources are 398335.49×10^{11}KJ according to the lower recovery rate of 0.05, which equivalent to 13.61×10^8t of standard coal. If the above geothermal resources are fully utilized, the carbon dioxide emission reduction can be achieved by 33.93× 10^8t.

Table 1 Survey parameters of geothermal resources in exploration area of western Sichuan Basin

Geothermal field (oil field)	Block		Stratum	Area (km^2)	Reservoir lithology	Types of reservoir	Formation water temperature/ average temperature (°C)	Wellhead temperature/ average temperature (°C)	Formation water depth/average depth（m）	Average geothermal gradient (°C/100m)	Thickness of aquifer/average thickness (m)	Porosity/average porosity (%)	Permeability/average permeability (md)	Formation water density (kg/m^3)	The heat capacity of formation water (J/(kg·°C))	Density of geothermal reservoir rocks (kg/m^3)	The heat capacity of geothermal reservoir rocks (J/(kg·°C))	Reference temperature (°C)
Exploration area of western Sichuan Basin	Piedmont belt	Dayi	Penglaizhen Formation	901.2	Sandstone	Pore +fracture	41-73/54		1050-2542/1650	2.13	73-148/110	1.13-19.39/10.51	0.024-19.21/1.076	1010	4200	2310	894	16
			Shaximiao Formation	901.2	Sandstone	Pore +fracture	65-93/79		2200-3500/2850	2.13	143-210/180	1.02-16.75/12.53	0.003	1010	4200	2470	894	16
			The fourth member of Xujiahe Formation	901.2	Sandstone	Pore +fracture	97-104/101		3700-4000/3850	2.13	48-118/80	1.07-3.04/1.57	0.003-0.075/0.02	1090	4200	2560	894	16
		Yazihe	Shaximiao Formation	876.2	Sandstone	Pore +fracture	39-63/53		1100-2000/1600	2.1	180-307/250	6.9-11.9/9.8	0.26-0.8/0.57	1010	4200	2430	894	16.1
			The fourth member of Xujiahe Formation	876.2	Sandstone	Pore +fracture	70-92.5/80		2400-3500/2800	2.1	230-440/300	0.65-10.17/5.03	< 0.01-1.36/0.25	1010	4200	2560	894	16.1
		Anxian	Shaximiao Formation	197.3	Sandstone	Pore +fracture	39.5-66/50		1180-2500/1800	2.01	45-248/180	6.9-11.9/9.8	0.26-0.8/0.57	1010	4200	2540	894	15
			The fourth member of	197.3	Sandstone	Pore +fracture	56-67/62		2150-2600/2350	2.01	56-103/85	0.65-10.17/5.03	< 0.01-1.36/0.25	1010	4200	2540	894	15

			Xujiahe Formation															
			The second member of Xujiahe Formation	197.3	Sandstone	Pore +fracture	82-100/93		3260-4000/3700	2.01	160-315/260	0.87-8.38/4.26	< 0.01-12.31/0.35	1010	4200	2540	894	15
	Chengdu Depression		Cretaceous	3761	Sandstone	Pore +fracture	20-43/33		150-1300/800	2.06	150-200/176			1010	4200		894	16
			Penglaizhen Formation	3761	Sandstone	Pore +fracture	38-53/46	23-37/29	1000-2400/1700	2.06	140-200/166	1.13-19.39/10.51	0.024-19.21/1.076	1010	4200	2310	894	16
			Shaximiao Formation	3761	Sandstone	Pore +fracture	61-84/73	41-64/53	2300-3400/2900	2.16	200-300/240	1.02-16.75/12.53	0.026-2.989/0.737	1020	4200	2470	894	16
			The fourth member of Xujiahe Formation	3761	Sandstone	Pore +fracture	93-105/99	73-85/77	3500-4000/3900	2.23	300-400/350	1.2-6.89/4.55	0.002-10.25/0.7246	1050	4200	2560	894	16
	South-north Tectonic Zone		Penglaizhen Formation	1488	Sandstone	Pore +fracture	27-53/40		400-1500/900	2.2	120-200/150	4-18/12	0.1-1.5/0.7	1010	4200	2290	894	16.5
			Shaximiao Formation	1488	Sandstone	Pore +fracture	53-81/66		1500-2700/2000	2.3	210-290/245	0.48-16.02/8.31	0.001-1.997/0.178	1020	4200	2340	894	16.5
			The fourth member of Xujiahe Formation	1488	Sandstone	Pore +fracture	93-110/100		3200-4000	2.3	350-500/400	3.28-11.10/5.26	0.060-2.412/0.55	1050	4200	2500	894	16.5

	NEE Tension Block	Penglaizhen Formation	1600	Sandstone	Pore +fracture	36-56/46		300-1600	2.06	140-180/160	4-18/12	0.1-1.5/0.7	1010	4200	2310	894	16.1
		Shaximiao Formation	1600	Sandstone	Pore +fracture	56-80/68	36-60/48	1900-2700	2.6	40-60/50	2.48-13.54/5.6	0.1	1010	4200	2470	894	16.1
		The fourth member of Xujiahe Formation	1600	Sandstone	Pore +fracture	85-106/95	65-86/75	3200-4000	2.13-2.38	70-90/80	0.26-13.56/5.2	0.02-180.212/0.67	1010	4200	2560	894	16.1
	Zitong Depression	Penglaizhen Formation	1384	Sandstone	Pore +fracture	39-58/48		682-1805	2.4	34-167/145	6.5-10.4/8.5	0.11-0.36/0.23	1010	4200	2500	894	16.1
		Shaximiao Formation	1385	Sandstone	Pore +fracture	58-82/70		2240-3300	2.4	13-65/43	3.5-9.7/6.3	0.05-0.3/0.11	1010	4200	2350	894	16.1
		The fourth member of Xujiahe Formation	1386	Sandstone	Pore +fracture	82-102/92		3643-4058	2.4	23-175/142	1-6.3/4.4	0.01-0.1/0.05	1010	4200	2440	894	16.1

5 CONCLUSION

(1)The geothermal reservoirs with the buried depth is less than 4000m in the exploration area of western Sichuan Basin are mainly Cretaceous, Jurassic Penglaizhen Formation, Shaximiao Formation, and the fourth member of Xujiahe Formation, and the area with buried depth of less than 4000m in the second member of Xujiahe Formation at the Sichuan Basin margin (Anxian block of piedmont belt). The above geothermal reservoir rocks are all clastic (sandstone) geothermal reservoirs, which are pore and fracture-pore type rock, with porosity ranges from 3 to 14% and geothermal reservoir temperature ranges from 27 to 110°C.

(2) In this paper, conduction geothermal resources in exploration area of western Sichuan Basin are calculated by geothermal reservoir method. The geothermal resources in the exploration area of western Sichuan Basin is 7966709.87×10^{11}KJ, which are equivalent to 272.18×10^{8}t of standard coal. There are recoverable geothermal resources 398335.49×10^{11}KJ according to the lower recovery rate of 0.05, which equivalent to 13.61×10^{8}t of standard coal. If the above geothermal resources are fully utilized, the carbon dioxide emission reduction can be achieved by 33.93×10^{8}t.

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