Heliyon 8 (2022) e12123

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Research article

The situation analysis of hot dry rock geothermal energy development in China-based on structural equation modeling

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A R T I C L E I N F O

Keywords:
Hot dry rock
Geothermal energy
Structural equation model
Peak emissions
Carbon neutrality

A B S T R A C T

In order to combat climate change, China proposed a dual carbon target in 2020. (China's 2030 and 2060 Goals). If the goals can be achieved as scheduled, it will help the world achieve the carbon neutrality goal earlier and improve the increasingly serious global climate. Reducing the utilization of fossil fuels and increasing the share of clean energy in primary energy are major ways to achieve China's 2030 and 2060 Goals. As a geothermal resource with large reserves, high energy storage, clean and pollution-free, dry hot rocks can effectively contribute to the goals. To promote the utilization of dry hot rock, this paper quantitatively studies the factors affecting the development and utilization of dry hot rock, and first summarizes five major influencing factors, namely, resources, environment, market, exploration and development technology, and effective use of technology. Then questionnaire survey based on these five factors was designed and distributed by email to geothermal energy experts in universities (China University of Geosciences, etc.) and research institutions (Chinese Academy of Sciences, etc.). Finally, the questionnaires are subjected to a reliability credibility test and validity analysis to remove the non-conforming items, and the structural equation model was constructed to analyze the data. The results show that environment, market and exploration and development technology have significant effects on dry hot rocks, while resources and effective use of technology have insignificant effects on dry hot rocks. Finally, some suggestions to promote the development of dry hot rocks in China are proposed.

1. Introduction

China has become the world's largest carbon emitter since 2006 [1]. And a large amount of carbon dioxide is emitted every year, accounting for 28% of the world total in 2017 [2].

In order to combat climate change, China proposed a dual carbon target in 2020, namely reaching carbon peak by 2030 and achieving carbon neutrality by 2060 (China's 2030 and 2060 targets) [3]. Carbon neutrality means that emissions can be reduced in various ways, such as the utilization of low-emission tools and reforestation. These reductions can be offset against generated carbon, achieving “zero” carbon emissions.

Climate change is a global issue. Greenhouse gases are growing rapidly with CO_2 emitting. Greenhouse gases are gases in the atmosphere that absorb long-wave radiation reflected from the ground and re-emit it, such as water vapor, carbon dioxide, and most refrigerants. Their effect is to make the earth's surface warmer, similar to how a greenhouse traps solar radiation and heats the air inside. This effect of greenhouse gases making the earth warmer is called the "greenhouse effect". As a result, a series of issues emerge, such as increasing surface temperatures, nature's food chain is breaking down and so on, which seriously disrupt the ecological balance [4, 5]. Therefore, countries are reducing emissions by employing a global compact to reduce the growth rate of greenhouse gases.

Based on this, China's 2030 and 2060 Goals are proposed. To achieve this goal is not only what China needs for its own sound development, but also its responsibility as a major country. In addition, it is also a demonstration of China's determination to reduce emissions.

In order to reduce emissions effectively, clean energy must be used to replace the traditional fossil energy. Geothermal energy is a substitute for fossil energy used for heating in the north of China. In 2015, the heating area in northern China reached 1.32 billion square meters, and the total energy consumption reached 100 million standard coal [6]. In 2018, the amount of CO_2 emissions from urban heating alone reached 550 million tons, which is equivalent to 210 million tons of standard coal [7]. Therefore, China needs to search for clean and renewable energy sources to replace the fossil energy.

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https://doi.org/10.1016/j.heliyon.2022.e12123
Received 27 May 2022; Received in revised form 11 July 2022; Accepted 28 November 2022

Hot dry rock is an emerging geothermal energy source with huge energy, its temperature is generally between 150 °C–650 °C, and it is buried 3–10 km underground [8]. In addition, the dry hot rocks are dense high-temperature rock mass with no or little liquid. It is estimated that the total heat of dry hot rocks buried underground is 30 times more than the total amount of fossil energy, and the total heat storage can reach 2.52×10^{25} J in China [8].

Dry hot rock exploitation can be divided into the following processes: First, a "water injection well" is drilled into the dry hot rock from the surface. Second, high pressure and low-temperature water are injected from a closed wellhead. The high-water pressure creates cracks in the rock formation, gradually forming a faceted thermal storage structure. Third, several "production wells" are drilled from the surface downward, where steam and high-temperature water are recovered to the surface. High-temperature steam can be used for heating and electricity generation. Finally, the remaining warm water will be returned to the dry hot rock through injection wells, thus enabling energy recycling. Dry hot rock, a renewable geothermal resource, contains a lot of energy.

In addition, dry hot rock can solve the energy shortage and realize green and sustainable development. Compared with other renewable energy sources, dry hot rock has its unique advantages, such as its exploitation is not affected by the natural environment [9, 12]. Once large-scale development is achieved, its cost will be lower than that of renewable energy sources such as solar and wind. Therefore, the development and utilization of dry hot rock can make China's 2030 and 2060 Goals achieved at an early date.

As early as the 1970s, the idea of utilizing the heat in underground rocks, that is, dry hot rock, was proposed in the United States. The real kick-off of dry hot rock exploiting was in 1972 when the first well was drilled in Mexico, and since then the U.S. has increasingly invested in dry hot rock. By 2016, dry hot rock investment in the United States totaled nearly $450 million. After 2000, the U.S. began to adopt enhanced geothermal systems (EGS), and significant progress was made, with dozens of EGS projects completed. The technology is relatively mature in the U.S., with wells drilled to depths of 4,390m and bottom hole temperature of 327 °C in recent years [10].

After the United States, the United Kingdom and Japan began to study hot and dry rocks. The UK was the first to develop dry hot rock in Cornwall, and the test still ranks the world's second. In the 1980s, Japan began a feasibility study of dry hot rock development in Yamagata Prefecture and has conducted several tests since then. At the end of the 20th century, Japanese wells were drilled to a depth of more than 2 km, with bottom hole temperature reaching about 250 °C [11]. The Australian research on dry hot rock is relatively late compared to the U.S. and was formally tested in 2003. Combined with the previous EGS project, satisfactory results were achieved, with wells drilled to a depth of 4.5 km and bottom hole temperature 20 °C higher than Japanese Geothermal project [11].

In terms of research on dry hot rocks, China is in its infancy compared to other countries. In 2010, China first started to survey on dry hot rocks. In 2014, China implemented its first dry thermal rock clean energy heating project in Qingdao. The project used well network fracturing and U-shaped wells to extract the temperature from the dry hot rocks. The drilling depth is nearly 3 km, and the temperature has about 180 °C [11]. Using this project for heating, the room temperature can reach more than 23 °C, while improving the air quality of Qingdao, reducing the impact of acid rain and greenhouse effect. In 2015, China discovered dry hot rock resources in Fujian and Heilongjiang and then conducted drilling to a depth of 4 km [11].

The utilization of dry hot rock in China is in the preliminary stage and the development prospect is optimistic. However, the influencing factors of dry hot rock development are still unclear. To accelerate the pace of dry hot rock utilization and achieve China's 2030 and 2060 Goals, this paper will explore the constraints in the development process of dry hot rocks through questionnaires. And the respondents include experts related to geothermal energy from universities and research institutions. The data obtained through the questionnaire will be analyzed by structural equation modeling to find out the main factors limiting the development of dry hot rock. In addition, this paper will provide suggestions for the government and enterprises to drive the development of dry hot rocks in China and thus reduce greenhouse gas emissions.

This paper has the following innovations:

1. Various and comprehensive influencing factors are considered.

At present, most articles on dry hot rock focus on single factors affecting the development of dry hot rock, such as technology. Considering from the aspects of resources, environment, market and technology, this paper combines these influencing factors to study the interaction between these factors and their impact on the development of dry hot rock. Consider from many aspects.

2. Study dry hot rock from a quantitative point of view

This study helps to fill the gap in the field of research related to dry hot rock development. In China, most of the existing studies related to dry hot rock are qualitative analyses. In this study, a quantitative analysis is adopted, which fills the gap in the field of dry hot rock research in terms of quantification. The research on dry hot rock at home and abroad is mainly quantitative research on technology, and the impact on resources and environment is studied in a qualitative way. Combined with qualitative and quantitative methods, this paper makes a qualitative analysis on the influencing factors of dry hot rock development by using the questionnaire survey method. Then the structural equation model is used for quantitative research, so that each influencing factor has been analyzed both qualitatively and quantitatively. Make the research results more comprehensive and reliable.

2. Literature review

According to relevant literature, the main factors affecting the development and utilization of dry hot rock are resources, environment, market, exploration and development technology and effective utilization technology.

2.1. Resources

Resource factors include reserves, distribution, renewable and development stability.

It is reported that the total heat of hot dry rocks in China reaches 2.52 × 1025 J [8]. The amount of energy reserves directly determines whether energy can be developed and utilized on a large scale.

Hot and dry rocks are mainly distributed in areas with relatively active plate activity, such as volcanic eruption sites, mainly distributed in the Qinghai-Tibet Plateau (southwest China), Songliao Basin (Northeast China), Bohai Bay Basin (East China) and southeast coast [13, 15, 16]. The distribution of dry hot rock is relatively dispersed, which is not conducive to centralized mining, and more Wells need to be drilled for mining, which increases the mining cost and is not conducive to the marketization of dry hot rock resources.

Dry hot rock is clean, environmentally friendly and renewable in use, does not emit greenhouse gases, and can be used in a variety of ways, such as heating, power generation and agriculture [14]. Dry hot rock only produces water in the process of use without any pollution to the environment, which can not only solve the problem of energy shortage, but also help to reduce carbon emissions and contribute to the future development of dry hot rock. In addition, influenced by the substitution of fossil energy and the global pursuit of energy diversification [17], it is believed that dry hot rocks have large reserves, are safe and pollution-free, and should be used globally [18].

2.2. Environment

Environmental factors include seismic problems, water availability, rock conditions and groundwater contamination.

Currently, the widely used fracturing technology is hydraulic fracturing, which may cause geochemical problems and easily induce earthquakes [19, 20]. The Basel project in Switzerland was halted after residents objected to earthquakes caused by the project. Therefore, the seismic problems caused by dry hot rock mining will affect the development of dry hot rock in the future.

Both hydraulic fracturing and the construction of heat storage reservoirs require large amounts of water. Using the ORC power plant model, Some scholars [21] found that water is more suitable as a thermal fluid than hot oil. Some scholars [22] studied the influencing factors of shale gas development and utilization using structural equation model, and pointed out that China is a water-scarce country, especially in northern China, where two-fifths of the population only depends on one-fifth of the country's fresh water resources. This is a challenge to dry hot rock development.

With the increase of temperature, the mechanical properties of dry hot rocks deteriorate, and the long compression end of rocks brings many difficulties to reservoir modification technology [23, 24]. The roughness of rock will affect the stability of rock. Some scholars [25] Hot and dry rocks may occupy a large amount of land and even destroy forests in the process of development. In addition, groundwater is polluted during heat exchange between water and rocks [26].

2.3. Market

Market factors include the demand for clean and sustainable energy, the price of electricity generation, the regulatory regime for hot dry rock and the willingness of investors.

China's rapid urbanization and rising demand for clean heating in northern regions have led to an increasing demand for clean energy. Global temperatures are rising as fossil fuel use increases, and the most immediate solution is to use renewable energy [27, 28, 29, 30].

Geothermal energy has great potential and strong cost competitiveness. However, the initial investment of dry hot rock is higher than the cost of wind and solar power generation, and the current immature technology leads to high initial power generation cost and weak market competitiveness. Therefore, government policy assistance is needed (Arman and Christian, 2020; Wang et al., 2020; Li et al., 2015) [26,31,35].

The United States, Japan and other countries have a series of policy support for the development and utilization of dry hot rocks, such as subsidies and tax deductions for geothermal power generation [32]. The United States generates nearly 15 GW of geothermal energy annually [33]. In 2013, geothermal energy accounted for 0.3% of Japan's total electricity generation [34].

2.4. Exploration and development technology

The factors of exploration and development technology include resource exploration technology, high temperature drilling technology, artificial reservoir construction technology and anti-corrosion and anti-resistance technology.

Under the action of high temperature and pressure, the mechanical conditions of the rock will change, leading to the contraction and collapse of the borehole. Therefore, high temperature and high-pressure environment has more stringent requirements on the bit [13, 36, 37]. As a result, various studies have been conducted on how to improve bit performance [36, 38].

The development and utilization of hot and dry rocks requires fluid circulation between injection and production Wells, thus requiring well fractured reservoirs to allow efficient fluid penetration into the formation [39, 40]. There are three main methods of reservoir modification: hydraulic fracturing, thermal fracturing, and chemical strengthening [41]. Deep underground geothermal energy exploration technology is the key to the discovery of dry hot rocks, but the current exploration level in China still lags behind the international level [17].

Water is not only a highly polar solvent, but also easy to react with chemicals in rocks, forming sediments and other substances, blocking pipelines and limiting the efficient utilization of geothermal resources [42, 43].

2.5. Effective use of technology

The technical factors of effective utilization include the construction of underground heat storage reservoir, dry hot rock dynamic supervision system, power generation grid connection and tailing water recharge technology.

Building a reservoir in granite can increase the heat transfer area of water and rock in the reservoir, improve the heat transfer efficiency, and reduce the cost to a large extent [23, 44, 45]. But building an artificial reservoir is difficult. At present, the development level of geothermal resources in China is low, with loose management, lack of standardized and dynamic supervision system, and insufficient development and utilization [32, 54].

Renewable energy grid-connected power has volatility and uncertainty, and its permeability in power system is constantly increasing, which brings new challenges to power supply security [46]. Some scholars [47] believed that power generation cost and power supply characteristics could be used to determine the proportion of different energy sources in the future power system to solve this problem. Some scholars [63] proposed an energy storage demand analysis method based on system operation bottleneck identification.

2.6. Summary

In summary, resources, environment, market, exploration and development technology, and effective use of technology are all influencing factors in the process of dry hot rock development and utilization in China. Compared with countries such as the U.S. and the U.K., which have mature technologies and methods, China is late in developing dry hot rocks and is in its infancy in all aspects. To better understand the degree of influence of different factors on dry hot rock, a questionnaire survey and structural equation model are adopted to analyze the influencing factors, and both methods are frequently applied in the medical and energy fields.

3. Hypothesis

Based on the literature review, in order to further understand the impact of resources, environment, market, exploration and development technology and effective utilization of technology on the future development of dry hot rocks in China, the following hypotheses are proposed, as shown in Figure 1.

4. Methods and data

4.1. Questionnaire survey

Questionnaire survey refers to a method in which the respondents answer the questions in a carefully designed questionnaire so as to collect data and materials and discover the current situation of facts. The questions in the questionnaire mainly revolve around the questions to be studied. According to the different carriers, it can be divided into paper questionnaire and network questionnaire.

4.2. Questionnaire design and data collection

To make obtained data more realistic and reliable to reflect the real situation, a combination of methods was applied to design the

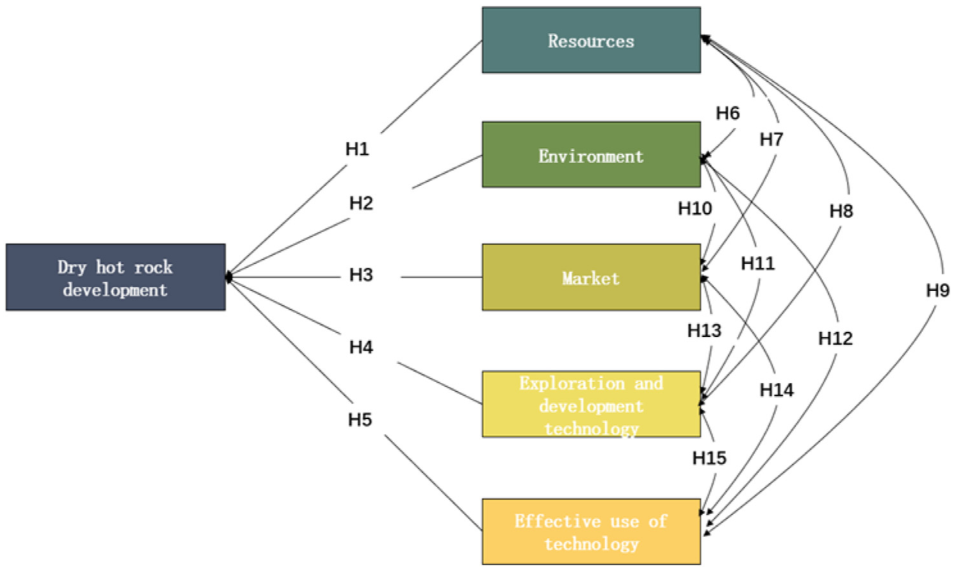

Figure 1. Research factors and hypotheses.

questionnaire. First, the existing literature was collated and summarized, and the first draft of the questionnaire was designed by collecting information from various aspects; then, the first draft was discussed with industry experts, and the final questionnaire was revised and improved according to the results of the discussion. The questionnaire has 28 questions, among which 5 are about basic information of the respondents, and the survey part of the dry heat rock influence factors uses a multi-item scoring system with a total of 7 points. 1 means totally disagree, 7 means totally agree, and the degree of agreement increases from 1 to 7 in order (See appendix for specific questionnaire questions).

Data were collected by means of questionnaires, which were directly mailed to experts related to geothermal energy in famous universities (China University of Geosciences, etc.) and research institutions (Chinese Academy of Sciences, etc.). These experts have been working on geothermal energy for a long time and have a deep understanding of geothermal energy. A total of 1067 questionnaires were sent out, and 235 were effectively received with a recovery rate of 22.02%.

4.3. Structural equation model (SEM)

Structural equation model (SEM) is an important tool for multivariate data analysis. Its principle is to analyze the relationship between variables based on covariance matrix. The variables (in this paper, the influencing factors of dry hot rock development) are not easy to be measured directly and accurately, and need to be measured indirectly with the help of other observable indicators, so they are called latent variables. Structural equation contains explicit variable and latent variable, and can be used to analyze the relationship between explicit variable and latent variable as well as latent variable.

The function of measurement model in this study is as follows:

$$x = \Lambda_x \xi + \varepsilon \quad (1)$$

Table 1. Cronbach's ɑ reliability coefficient evaluation table.

Cronbach ɑ reliability coefficient	Reliability
>0.8	High
0.7–0.8	Good
0.6–0.7	Acceptable
<0.6	Poor

where x denotes exogenous observation variable; Λ_x represents the factor loading matrix of the x; ξ is exogenous potential variable; ε is residual vector of the equation. The function of structural model in this study is as follows:

$$y = \Lambda_y \eta + \varepsilon \quad (2)$$

where y denotes endogenous observed variable; Λ_y represents the factor loading matrix of the y; η is endogenous latent variable; ε is residual vector of the equation. The function of structural equation model in this study is as follows:

$$\eta = \mathrm{B}\eta + \Gamma\xi + \zeta \quad (3)$$

where η is endogenous latent variable; B denotes path coefficient of the endogenous potential variable; Γ represents the path coefficient of the exogenous potential variable; ξ is exogenous potential variable; ζ is residual vector of the equation.

4.4. Sample descriptive statistics

From the samples obtained, 94.29% were mainly male, while only 5.71% were female, which may be due to the fact that geology, petroleum engineering and other majors are dominated by males. From the perspective of educational background, they all have master's degree or above. Doctor's degree is the main part, accounting for 94.29%, while master's degree is only 5.71%. It can be seen that most of the samples are highly educated talents.

From 20 to 69 years old, the samples were divided into five gradients. The samples were mainly concentrated in 30–49 years old, accounting for 74.28%, among which, 30–39 years old accounted for 45.71%, and 40–49 years old accounted for 28.57%. There were as many people aged 20 to 29 as 60 to 69, both accounting for 2.86 percent, while the remaining 20 percent were aged 50 to 59, a relatively young age mix.

The major distribution of the investigated subjects can be divided into four categories: geology related majors, petroleum engineering related majors, energy management related majors and others. From the perspective of majors, the samples are mainly concentrated in geology related majors, accounting for 48.57%, followed by petroleum engineering related majors 22.86%, energy management related majors only 11.43%, and the rest 17.14% are composed of other majors, such as mining engineering, surveying and mapping, etc. It can be seen that most of them are professionals related to geothermal energy.

Table 2. Evaluation table of KMO sample measures.

KMO sample measures	Factor analysis fitness
>0.9	Very fitness
0.8–0.9	Quite fitness
0.7–0.8	fitness
0.6–0.7	A little fitness
0.5–0.6	Slightly fitness
<0.5	Not fitness

Table 3. Factor loading.

Factors	Coefficient	CR
Resources		0.6505
R1	0.781	
R4	0.602	
Environment		0.6682
E1	0.691	
E2	0.635	
E3	0.573	
Market		0.6449
M1	0.672	
M4	0.751	
Exploration and development technology		0.6067
P1	0.626	
P4	0.851	
Effective use of technology		0.6826
U1	0.747	
U2	0.551	
U3	0.554	
U4	0.503	
Development of dry hot rock		0.6089
D1	0.728	
D2	0.519	
D3	0.497	

5. Research analysis

5.1. Reliability analysis

Before structural equation model analysis, reliability test of the questionnaire is needed to ensure that the survey results are true, stable and accurate. The less volatile the data, the more reliable it is. Cronbach ɑ reliability coefficient method is adopted in this paper. SPSS software was used for analysis, and the calculated results showed that Cronbach ɑ reliability coefficient was 0.829. Table 1 shows that the questionnaire has high reliability.

5.2. Validity analysis

In this paper, the validity test method is structural validity, and the judgment methods generally include KMO sample measure (as shown in Table 2), Bartlett sphere test and factor load coefficient. When the result of Bartlett's sphere test is zero, the null hypothesis is rejected and factor molecules can be carried out. SPSS software was used for analysis, and the output result was KMO sample measure 0.815, which was considered valid if it was greater than 0.5 [48], and Bartlett's sphere test was 0.

Variables R2, R3, EN4, P2, P3, M2 and M3 with absolute load less than 0.4 (Zhao et al., 2021) [49] were eliminated according to the factor load coefficient table output in factor analysis. After the validity analysis of the remaining variables, the KMO sample measure is 0.816, and the Bartlett sphere test is 0. The factor load is shown in Table 3. According to Tables 2 and 3, the sample after removing some variables is suitable for further analysis and the factor load coefficient basically meets the requirements.

According to Table 3, it is clear that factor loading coefficients of all variables are greater than 0.4 and all CRs are greater than 0.6 (Zhao et al., 2021). Therefore, all the variables in the table are suitable for further analysis.

5.3. Adjust hypothesis model

The structural equation model used in this paper is exploratory structural equation model. The construction of the model is based on

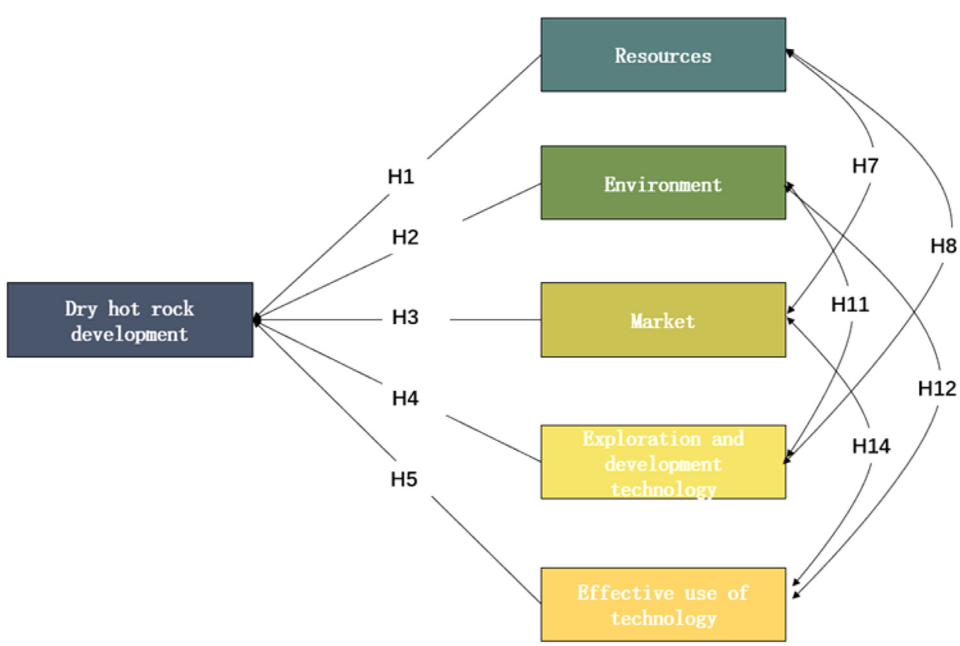

Figure 2. Research factors and hypotheses (excluding some hypotheses).

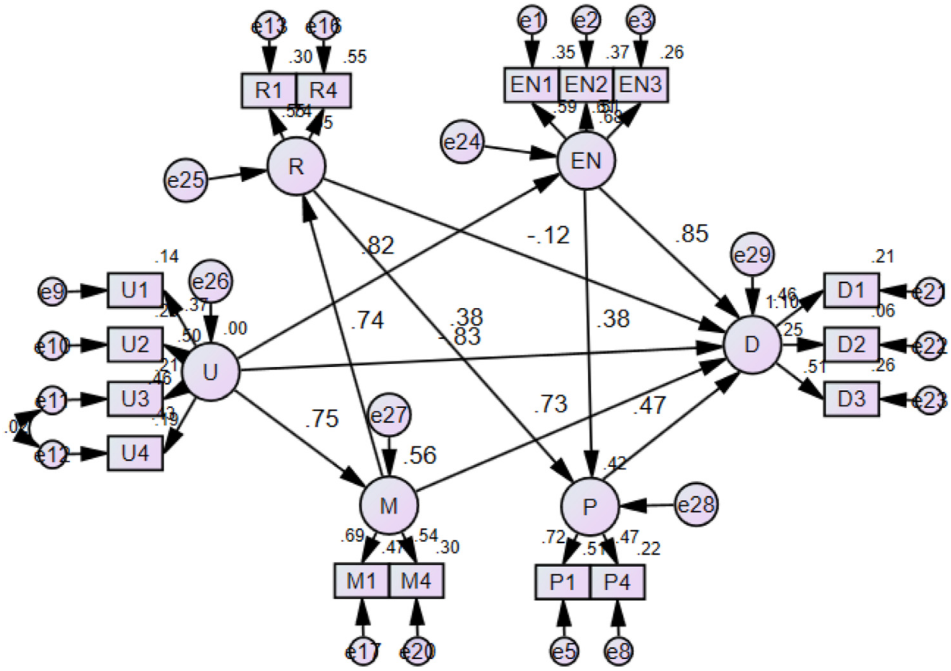

Figure 3. Structural equation model.

hypotheses, so a large number of hypotheses will be put forward based on literature, but some of these hypotheses may not exist. Therefore, several iterations are needed to determine the optimal hypothesis model. The questionnaire data were substituted into the exploratory structural equation model to screen the hypotheses, and hypotheses 6, 9, 10, 13 and 15 were finally eliminated. The eliminated hypothesis model is shown in Figure 2 below.

5.4. Confirmatory factor analysis

The structural equation models of R1, R4, EN1, EN2, EN3, M1, M4, P1, P4, U1, U2, U3, U4, D1, D2 and D3 are constructed by AMOS software. Adjust the model according to the output MI results. The CFA index value output by the software is used to judge whether it needs to be iterated again. The final result of the model is shown in Figure 3. R1, R4, EN1, EN2, EN3, M1, M4, P1, P4, U1, U2, U3, U4, D1, D2 and D3 are observed variables, while R, EN, M, U and D are potential variables.

Table 3 shows the fitting index parameters of the model and the evaluation criteria of each index. The Table 4 shows that the GFI, AGFI, IFI, and CFI are all greater than 0.900; the RMSEA is 0.043, which is less than 0.050; and the Chi-square degree of freedom is 1.434, which is between 1 and 3. All of the above is in conformance to requirements. According to Table 4, it can be drawn that all the indicators are up to standard, therefore the model is in good fitting degree.

GFI refers to goodness of fit test or fitness test. The GFI is given by

$$\mathrm{GFI} = 1 - \frac{\widehat{F}}{\widehat{F}_b} \tag{4}$$

where $\widehat{F}$ is the minimum value of the discrepancy function and F b is obtained by evaluating $\widehat{F}_b$ with $\sum(n) = 0$, n = 1, 2..., N. The author calculated that the Model's GFI is 0.934.

The AGFI is given by

Table 4. Fit index of the model.

Index	Indicator	Fitting index value	Criterion	Model fitting
Absolute fitness	GFI	0.934	≥0.900 is optimal, ≥0.800 is acceptable	Conform
	AGFI	0.903	≥0.900is optimal, ≥0.800 is acceptable	Conform
	RMSEA	0.043	≤0.050	Conform
	CMIN/DF	1.434	1–3	Conform
Simplified fitness	PCFI	0.718	≥0.500	Conform
	PNFI	0.620	≥0.500	Conform
	PGFI	0.638	≥0.500	Conform
Value-added fitness	IFI	0.929	≥0.900 is optimal, ≥0.800 is acceptable	Conform
	CFI	0.926	≥0.900 is optimal, ≥0.800 is acceptable	Conform
	TLI	0.904	≥0.900 is optimal, ≥0.800 is acceptable	Conform
	NFI	0.800	≥0.900 is optimal, ≥0.800 is acceptable	Conform

Table 5. Path coefficient and significance.

Path	S.E.	C.R.	P
D←R(H1)	0.201	-0.422	0.673
D←EN(H2)	0.334	1.731	0.084
D←M(H3)	0.277	1.790	0.074
D←P(H4)	0.196	2.088	0.037
D←U(H5)	0.564	-1.476	0.140
R←M(H7)	0.160	4.435	***
P←R(H8)	0.134	2.339	0.019
P←EN(H11)	0.115	2.572	0.010
EN←U(H12)	0.274	4.435	***
M←U(H14)	0.285	3.893	***

Note 1: "***" means that the regression coefficient of this path is significant at 0.001 level.

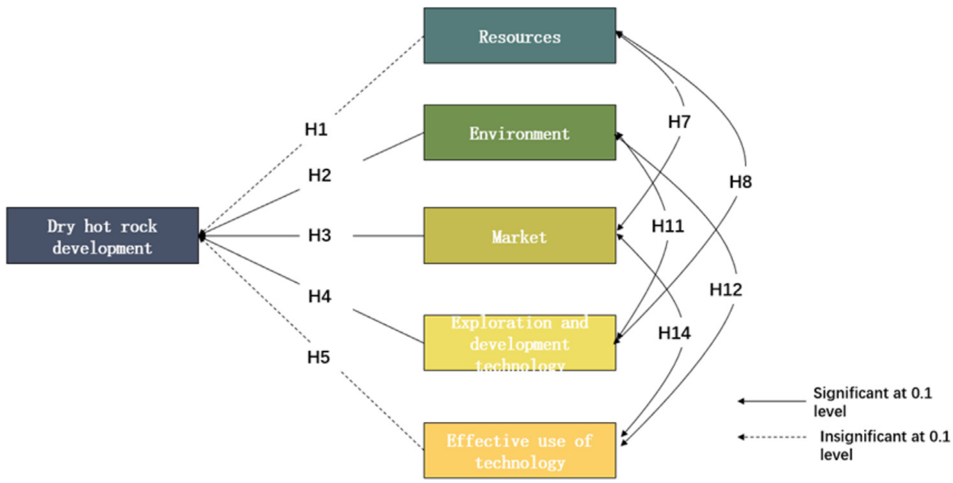

Figure 4. Final theoretical model.

$$AGFI = 1 - (1 - GFI)\frac{d_b}{d} \quad (5)$$

Where $d_b = \sum_{n=1}^{N} P^{(n)}$

The author calculated that the Model's AGFI is 0.903.

Overall, our model exhibited a reasonable fit with the data collected. Authors assessed the model fit using other common fit indices: GFI, AGFI, RMSEA, NFI and so on. The model exhibited a fit value exceeding or close to the commonly recommended threshold for the respective indices, the commonly suggested valued be list in Table 4.

6. Results

After the analysis of the data, a suitable structural equation model was constructed. According to the path diagram in Figure 3 and the significance in Table 5, Hypothesis 2, Hypothesis 3, Hypothesis 4, Hypothesis 7, Hypothesis 8, Hypothesis 11, Hypothesis 12, and Hypothesis 14 were supported, while Hypothesis 1, Hypothesis 5, Hypothesis 6, Hypothesis 9, Hypothesis 10, Hypothesis 13, and Hypothesis 15 were not supported, as shown in Figure 4.

6.1. Direct influence

The path analysis shows that the path coefficient of environment and development of dry hot rocks is positive and significant ($p = 0.084$) at 0.1 level; therefore, H2 is supported. The path coefficient of market and development of dry hot rock is positive and significant ($p = 0.074$); therefore, H3 is supported. The path coefficient of exploration and development technology and development of dry hot rocks is positive and significant ($p = 0.037$). Therefore, H4 is supported. In summary, environment, market, and exploration and development technology have a direct influence on dry hot rocks.

6.2. Indirect influence

According to the results of several iterations, the assumption of indirect influence between the efficient utilization of resources and technology was eliminated. Resources will affect exploration and development technology ($P = 0.019$), and effective use of technology will affect environment (P = *** (* means that the value is too small and the software does not show the figure)), and market (P = *** (* means that the value is too small and the software does not show the figure)). Finally, it is concluded that resources, effective use of technology have an indirect influence on dry hot rocks by influencing the environment, market, and exploration and development technology.

7. Conclusion

1. The influence of environment, market and exploration and development technology on the development of dry hot rock is significant, the influence degree of environment is 0.849, the influence degree of market and exploration and development technology is 0.734 and 0.474, respectively.

Compared with environmental and market factors, exploration and development technology is slightly weak for the future development of dry hot rocks. It may be because although China is still in the initial stage of exploration and development technology, foreign technology development in this area has been very mature. China can overcome this difficulty to a certain extent by learning foreign experience and introducing talents. Environmental and market factors are a major problem for the future development of dry hot rock for almost all countries and regions.

2. Resources and efficient utilization technology have no significant influence on the development of dry hot rock. The reason why the dry hot rock reserves are not significantly affected by resource factors may be that the dry hot rock reserves are nearly 30 times of the global fossil energy, and the distribution of dry hot rock is relatively concentrated, especially in southwest, northeast and southeast coastal areas of China.
3. In terms of environmental factors, the maximum path coefficient between rock conditions and environmental factors is 0.607; The path coefficient between water resource factor and environmental factor is 0.594. Finally, the path coefficient between seismic problems caused by hydraulic fracturing and the environment is 0.513.
4. In terms of market factors, the maximum path coefficient between China's demand for clean and sustainable energy and market factors is 0.689; The second is the investment intention of investors, including the amount of capital, investment risk, etc., and its path coefficient is 0.544.
5. In terms of exploration and development technology, the maximum path coefficient between the exploration technology of dry hot rock resources in China and exploration and development technology factors is 0.715. The second is the anti-corrosion and anti-resistance technology of pipeline, heat exchanger and other devices in the development process of dry hot rock, and its path coefficient is 0.473.

The results of the study provide a measurement model from a scholar's perspective. In addition, some contributions are made to other researchers studying on dry hot rocks.

8. Suggestions

Based on the above analysis results, the following suggestions are proposed:

1. In terms of environmental factors, China is a water-scarce country, and the hydraulic fracturing technology used in the development of dry hot rocks and the heat exchange process of water rocks require large quantities of water resources. At present, scholars both in home and abroad are studying the use of alternative water to extract the thermal energy contained in dry hot rocks, which will solve the problem of water use in the process. In addition, and it has important significance for geological storage.

The process of hydraulic fracturing can cause serious seismic problems by changing geology. Departments should pay attention to the process of exploiting and strengthen earthquake monitoring to prevent unnecessary casualties and property damage. At the same time, regulations should be clarified, the self-protection awareness of the public should be strengthened, and earthquake-related knowledge should be popularized. As for the influence of rock conditions on the development of dry hot rock, it is suggested that scholars should conduct research on the different mechanical properties of rocks as the temperature rises to find the optimal method for exploiting.

2. As for the market factor, the phenomenon of high investment with low or even no return has seriously discouraged investors' willingness to invest in dry hot rock. Therefore, the government and departments should introduce policies to encourage enterprises to invest in dry hot rock.
3. China is still at a low level in exploration and development, especially in the western areas where unexplored areas existed. Considering the shortage of exploration personnel in China, it is recommended to increase the efforts to train talents in resource exploration. In the process of heat exchange between water and rocks, water is prone to chemically react with rocks, and the substances generated after the reaction are easy to corrode and block pipes, heat exchangers, and other devices, which not only lowers the efficiency of mining and utilization, but also increases the cost of mining. Therefore, we hope that the departments will further study and explore corrosion and fouling of pipes and heat exchangers.

Declarations

Author contribution statement

Zhengwei Ma: Conceived and designed the experiments; Performed the experiments; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Li Peng: Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Jing Li: Analyzed and interpreted the data; Wrote the paper.

Lili Wu: Contributed reagents, materials, analysis tools or data; Wrote the paper.

Funding statement

Dr. Zhengwei Ma was supported by Ministry of Education of the People's Republic of China, China [17YJC790107], Philosophy and Social Science Foundation of China, China [18BJY251].

Data availability statement

Data will be made available on request.

Declaration of interest's statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

Appendix

Table 1. Questionnaire measurement items

Variable	Measurement item	Reference	Mean (Variance)
Resource R	R1 I believe that China's dry hot rock reserves meet the basic conditions for large-scale development of dry hot rock	[50]	5.53 (1.644)
	R2 I think the resource distribution of hot and dry rocks in China will affect the large-scale development of hot and dry rocks in China.	[17]	5.31 (1.482)
	R3 I think the reproducibility of hot and dry rocks is an important reason for the large-scale development of hot and dry rocks in China.	[51]	4.93 (1.864)
	R4 I think the stability of dry hot rock is an important reason for the large-scale development of dry hot rock in China.	[52]	5.31 (1.864)
Environment EN	EN1 I believe that the heavy use of water resources in the development of dry hot rocks will inhibit the development of dry hot rocks in China.	[53]	4.96 (1.947)
	EN2 I believe that rock conditions (such as low permeability and high strength of granite, etc.) will inhibit the development of dry hot rocks in China.	[23]	4.89 (1.985)
	EN3 I believe that the use of hydraulic fracturing in hot, dry rock development will cause significant seismic problems in areas associated with hot, dry rock development.	[55]	5.17 (1.792)

Table 2. Questionnaire measurement items(continue)

Variable	Measurement item	Reference	Mean (Variance)
Environment EN	EN4 I believe that dry hot rock development will bring serious pollution problems to the dry hot rock-related mining areas (such as pollution of groundwater during heat exchange).	[26]	5.02 (1.649)
Market M	M1 I believe that China's need for clean and sustainable energy (President Xi Jinping has proposed to achieve carbon neutrality by 2060) is an important factor driving the development of hot dry rock.	[54]	4.69 (2.043)
	M2 I think the price of hot dry rock power generation will affect the enthusiasm of Chinese hot dry rock development enterprises.	[55]	5.09 (1.568)
	M3 I think the government's management and supervision mechanism of hot dry rock (power generation subsidy policy, etc.) is conducive to the development of hot dry rock in China.	[56]	5.87 (1.381)
	M4 I think investors' investment willingness (capital, risk, etc.) for the development of dry hot rock affects the development of dry hot rock in China.	[57]	4.96 (1.845)
Exploration and development technology P	P1 I believe that the exploration technology of hot and dry rock resources in China is an important factor affecting the large-scale development of hot and dry rock.	[58]	5.32 (1.407)
	P2 I think China's hot dry rock high temperature drilling technology is an important factor affecting the large-scale development of hot dry rock.	[10]	5.17 (1.672)
	P3 I believe that China's artificial dry hot rock reservoir construction technology (hydraulic fracturing, chemical stimulation, etc.) is an important factor affecting the large-scale development of dry hot rock.	[59]	4.89 (1.646)
	P4 I believe that the anti-corrosion and anti-resistance technology of pipes, heat exchangers and other devices in the development process of dry hot rock in China is an important factor affecting the large-scale development of dry hot rock.	[58]	5.31 (1.75)

Table 3. Questionnaire measurement items(continue)

Variable	Measurement item	Reference	Mean (Variance)
Efficient utilization technology U	U1 I believe that the construction of underground heat storage reservoirs is an important factor affecting the effective utilization of hot and dry rocks in China.	[23]	5.0 (1.801)
	U2 I believe that tail water recharge technology is an important factor affecting the effective utilization of hot and dry rocks in the development process of China.	[60]	4.85 (1.802)
	U3I believe that the construction of China's dynamic supervision system for dry hot rock (real-time supervision and full utilization of resources) is an important factor affecting the effective utilization of dry hot rock.	[54]	4.84 (1.766)
	U4 I think the problem of dry hot rock power grid connection (volatility, uncertainty) is an important factor affecting the effective utilization of dry hot rock.	[63]	5.23 (1.404)
Dry hot rock development D	D1 I think China is ready for dry hot rock development on a large scale.	[62]	4.79 (1.947)
	D2 I think dry hot rock will be one of the key directions of geothermal energy development in China.	[17]	4.81 (1.646)
	D3 I think dry hot rock will have a good development prospect in China.	[61]	4.98 (1.54)

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