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GEOLOGICAL AND DRILLING ASPECTS OF CONSTRUCTION AND EXPLOITATION GEOTHERMAL SYSTEMS HDR/EGS**

1. INTRODUCTION

One of the most important aspects of science are unconventional sources of energy, including geothermal energy [12]. Earth heat can be produced using geothermal waters [21], underground or surface waters heated in rockmass [22] or without water by use borehole heat exchangers [23], Hot Dry Rocks (HDR) and Enhanced Geothermal Systems (EGS) are the most untypical system, which utilizing Earth heat. Hot Dry Rocks is a geothermal system using heat of hot dry rocks, which is forced to circulate water or other fluid between the boreholes by applying hydraulic fracturing [30]. Similarly, the concept of Enhanced Geothermal Systems should be understood geothermal systems designed for using thermal energy from boreholes, which aim is acquisition thermal energy stored in the Earth (Fig. 1) by means of heat transfer medium introduced by injection wells [28]. In many cases, the name of HDR and EGS are used interchangeably. However, it should be remembered that in Enhanced Geothermal Systems (EGS) can occur natural inflows water from the surrounding rocks, but they are too small to be able to start traditional system, working as a geothermal doublet or triplet. These systems use the heat from the rocks (mostly granite), where are the temperatures above 100^{o}C [30]. The installations can use new wells drilled specially for the system [26] or old exploited oil wells, like borehole heat exchangers [24]. Last time drilling technology grow fast [20], costs of drilling reduced, so geothermal drilling will be more popular.

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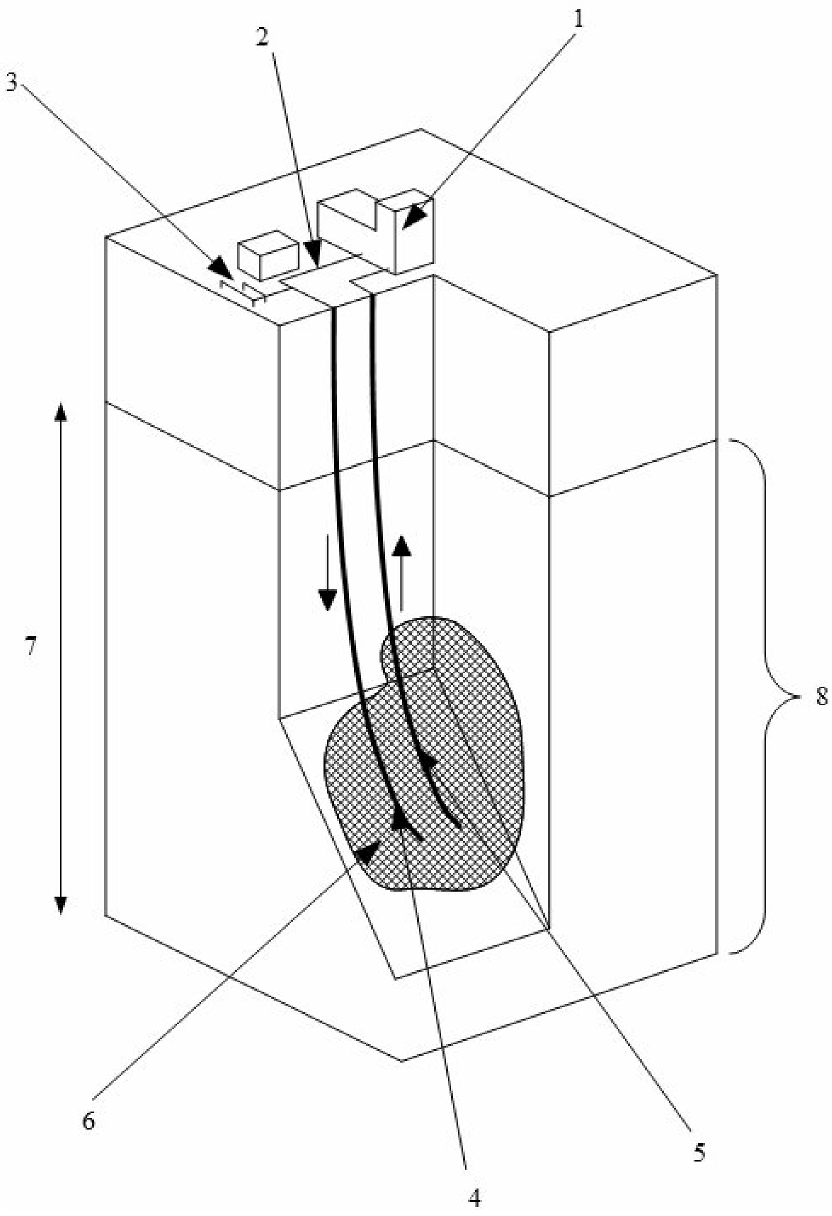

Fig. 1. Enhanced Geothermal Systems – own study based on. 1–8 see text [28]

A typical scheme of Enhanced Geothermal Systems shown in Figure 1. By means of injection pump (2), water from the tank (3) is introduced by injection well (4) to the reservoir, which is situated in at a depth of 3 to 10 km with low permeability rocks (8). Next the heated fluid by the production well (5) flows to the power plant (1). Wells are connected artificially by fracturing zone (6), resulting from treatments aimed at increasing the permeability of the rock mass [28].

Increase productivity the rock mass in both systems is obtained by the use of hydraulic fracturing. The heat from the fracturing rock heated water or other fluid flowing between the injection and production wells [30]. To create the possibility of circulating water between the boreholes in the poorly permeable or impermeable rocks it is necessary to create a fracturing zone. The success of the fracturing process is mainly conditioned by adequate preparation fluid and appropriate fracturing pressure. Injected fluid creates slot and transports the proppant. Aim of the proppant is to keep the slots before closing [25] after reduction of the pressure. It is also possible work system at high pressure in a continuous manner.

2. REALIZED PROJECTS

HDR/EGS projects have been known in the world since 45 years. Were performed lots of research in this time. Several projects after the study was completed. However, the results and experiences contributed to the development next systems. The method can be reasoned in the future, when the world prices energy will be stimulate a new ways of generating electricity and/or heat for heating purposes.

Fenton Hill, USA

First in the world project to use the heat of hot dry rock (granite) has been made in Fenton Hill in the United States of America. System concept was born in a laboratory in Los Alamos in 1970. Was planned increase heating productivity of the rock mass, by using hydraulic fracturing and the injection of water in a closed geothermal system. The project started in 1974 and consisted of two phases. The first phase was started in 1974 and continued for six years. At this time dealt with the development of the project and take research at depths up to 3 km, where the temperature of reservoir rocks was about 200°C. Was made the first well GT-2. Drilling started in February 1974 and was completed in September. Depth of the well was 2042 m. First hydraulic fracturing were performed in October. Next the well was deepened to 2932 m. Bottomhole temperatures were about 180°C. Borehole EE-1 was drilled in 1975, to a total depth of 3064 m and with a similar bottomhole temperatures as GT-2 (Tab. 1). In the period from June 1977 to December 1980 were made five tests of circulation. Was obtained heating power between 3 and 5 MW_t [28].

The beginning of the second phase is considered to 1979. Borehole EE-2 was drilled, to a total depth of 4400 m. Temperature of the rock was approximately 300°C. During the test in May 1986 years pumped into the borehole 37 thousand m^3 of water. Flow rates were between 10.6 and 18.5 kg/s, with between 26.9 and 30.3 MPa of pressure on the injection wellhead [28]. GEOTH3D Code was model used to simulate. GEOTH3D Code is a numerical model that simulates three-dimensional fluid- and heat-transport in porous media. Is used to model the behavior of a hot dry rock. It is composed of two equations based on Darcy's law [31].

Table 1

Presentation of selected completed projects HDR/EGS in the world [1,6, 8, 27, 28]

Name of the project	Period of activity	Name of the wells	Well depth, [m]	Rock type	Bottomhole temperatures, [^{o}C]	Thermal capacity	Stimulation methods	Model or software
Fenton Hill, USA	Phase I: 1974–1980 Phase II: 1980–1993	GT-2	2932	Crystalline rock	180 to 327	3 to 5 MW_t*	First hydraulic fracturing in 1974	Model GEOTH3D Code
		EE-1	3064					
		EE-2	4390					
		EE-3	about 4000					
Rosemanowes Quarry, United Kingdom	Phase I: 1976/77–1980 Phase II: 1981–1983 Phase III: 1984–1991/92	RH-11	about 2000	Granite	79 to 100	Research project, not geared for energy production	Use of explosives and fracturing	3-D fracture network model
		RH-12	about 2000					
		RH-15	2652					
Hijiori, Japan	1985–2002	SKG-2	1805 to 1910	Granodiorite	190	about 8 MW_t*	First hydraulic fracturing in 1988	Code FEHM (Finite Element Heat and Mass Transfer code)
		HDR-1						
		HDR-2 (2a)						
		HDR-3						

* Planned thermal capacity

Rosemanowes Quarry, United Kingdom

The second research project in the world, called Rosemanowes Quarry, was formed in the United Kingdom. The project started in 1977. Camborne School of Mines undertook an experimental hot dry rock. It consisted of three phases. As the reservoir rocks used the Carnmenellis granite. They are characterized by a high potential heat flow in this region [28]. Other authors of publications, such as Haring [6], give as the beginning of the first phase of the project in 1976, when it first information about drilling.

Was drilled three boreholes named RH-11 RH-12 and RH-15. Their depth ranged from 2000 to 2600 m. Research on the circulation and stimulation were conducted for more than 10 years. Developed and tested two systems composed of wells RH-11/RH-12 and RH-12/RH-15 [15, 28].

In the first phase of the project was made borehole to a depth of 300 m. His aim was to research about capacities and capabilities hydraulic fracturing. It was found, that the results at this depth are not representative. During the next phase drilled two boreholes: production RH-11 and injection RH-12. Bottomhole temperatures were about 79^{o}C (Tab. 1). In the lower borehole RH-12 were used stimulation methods – initially used explosives, and then hydraulically. The stream of liquid injection was to 100 kg/s and wellhead pressures of 14 MPa. In 1983, it was decided to drilling of the third well of the final depth of 2652 m, where recorded bottomhole temperatures around 100^{o}C. Hydraulic stimulation of the well was carried out similar to RH-12, with RH-12 continuing to be the injection well and RH-15 the primary producer. The experimental work was also carried out in the third phase of the project, which focuses mainly on choosing the optimal proppants [28].

Hijiori, Japan

New Energy and Industrial Technology Development Organization (NEDO) on the basis of the experience gained in the United States decided to use the technology developed in the Fenton Hill in relation to the geological conditions in Japan. The project was situated on the southern edge of Hijiori caldera, located in Honshu. The location was chosen to take advantage of the high temperature gradient. In this area was observed volcanic activity [28].

First injection well was drilled in 1989, called SKG-2. Casing 12 3/8" were run to a depth of 504 m, 9 5/8" to a depth of 1298 m and 7" to 1788 m. In the interval 1788–1802 m was open hole section at the bottom [14]. Three producers HDR-1, HDR-2 (named HDR-2a), and HDR-3 were drilled between 1989 and 1991. Natural fractures were intersected in all the wells at depths between 1550 m (temperature reached more than 225^{o}C) and 1800 m (the maximum temperature was close to 250^{o}C) depth. Distances at a depth of 1800 m between borehole SKG-2, and the other amounted to: 40 m to HDR-1, 50 m to HDR-2 and 55 m to HDR-3 [14, 28]. Then, successively deepening wells to take advantage of the heat of hot rocks located at a depth of about 2200 m. The final depth of wells are shown in Table 1.

The first hydraulic fracturing took place in 1988. Into the borehole SKG-2 was injected 2000 m^3 of water. The stimulation was carried out in four stages at rates of 1, 2, 4 and 6 m^3/min. A 30 day circulation test was performed in 1989 after stimulation. In the Table 2 indicates the hydraulic parameters longest circulation tests. In the next years were performed further stimulation treatment [28]. Some authors [1, 8] give the example of a project Hijiori as geothermal system is still running.

Table 2

Hydraulic parameters of the longest circulations in selected systems HDR/EGS [8]

Name of the project	Depth, [km]	Year	Well separation*, [m]	Circulation duration, [days]	Flow rate, [dm^3/s]	Reservoir Impedance, [$MPa/dm^3/s$]	Loss, [%]
Fenton Hill	2,8	1980	GT2a to EE1 200	282	5,5	1,7	10
Fenton Hill	4,2	1992	EE3a to EE2a 200±50	183	5,7	4,0	16
Rosemanowes	2,2	1988–1989	RH12 to RH11/RH15** 120/150-250	200	3/16	3,3-0,6	21
Hijiori	1,8	1991	SKG-2 to HDR-1/HDR-2 /HDR-3 40/50/55	90	12,8	0,4-0,7	23
Hijiori	2,2	200	HDR-1 to HDR-2a/HDR-3 90/130	300	5,8	1,4/2,1	64
Soultz	3,5	1997	GPK-1 to GPK-2 450	135	25	0,2	0
Soultz	5	2005	GPK-3 to GPK-2 600	150	12	0,6	0
Soultz	5	2005	GPK-3 to GPK-4 600	150	3	1,9	0
Soultz	5	2008	GPK-3 to GPK-2 600	60	25	~0,55	0
Habanero	4,2	2009	Habanero 1 to Habanero 3 560	60	17	0,7	0

* Injection well given first
** Production wells delimited by „/”

The literature also other completed projects HDR/EGS, which are described in very perfunctorily. These are: Ogachi in Japan, Falkenberg in Germany, Fjällbacka in Sweden, Bad Urach in Germany and Basel in Switzerland [1].

3. ONGOING PROJECTS

Studies on the exploitation of heat from hot dry rocks are long-lasting. Research projects often ongoing decades. Following describes projects HDR/EGS in progress.

Soultz, France

First formal sketch of the project was created in 1984. Project is located in a geothermal anomaly within the Upper Rhine Graben in Alsace. Heat reservoir constitute granites. Initially, the project was named European Hot Dry Rock (HDR) project at Soultz-sous--Forêts. After ascertaining that the fractured granite basement rocks o contained large volumes of hot saline fluid was renamed projects as an Enhanced Geothermal System in 2001. During the project several times stimulation tests were performed, including use of hydraulic fracturing [4, 8].

First drilling operations started in 1987. Was made the borehole GPK-1 to 2000 m. In 1990 was created a network of seismic observation wells using old oil wells. Two years later borehole GPK-1 was deepened to 3600 m, where temperature measured was 160^{o}C. In 1995 was started drilling of GPK-2. The well GPK-2 was deepened in the next years to a final depth 5010 m. Also made wells GPK-3 and GPK-4 to depth approximately 5100 m [4]. During project implementation in Soultz builds on the experience gained from other research projects HDR/EGS [28].

Groß Schönebeck, Germany

Project Groß Schönebeck is located in the Northeast German Basin. It is one of the most important geothermal projects in Europe. The special design of the system has been constructed in order to allow for access to the reservoir with logging tools during fluid production using a new developed Y-tool. To data recording has been developed combined measurements with electrical tools and fiber-optic distributed temperature sensing (DTS). The data transfer to surface is problematic and can only be done a discontinuous manner [1, 7].

Geothermal reservoir is at a depth of 4100 to 4300 m. The rock mass at this depth created mainly the permeable sandstones of the Upper Rotliegend (Dethlingen Formation) and volcanic rocks. Bottomhole temperatures situated at such a depth was about 150^{o}C (Tab. 3) [7].

In project was used injection well E GrSk 3/90 (formerly exploration borehole) and production well GtGrSk 4/05. Distance between the wells on the surface is 28 m, and between the bottoms of the boreholes is 470 m. The well casing, liner and tubing are constructed to be carbon steel with a constant thermal conductivity of 50 W/(m·K) [5, 7, 29].

In 2002 was started the hydraulic stimulation in one borehole. For most noteworthy treatment made in August 2007. Water in an amount of 13 thousand m^3 was injected through a cyclic procedure, ranging from 1.2 m^3/min up to 9 m^3/min into the permeable volcanic rocks Wellhead pressure needed to reach that flow was ranging from 30 MPa up to 58.6 MPa, while calculated minimum fracture pressure was 24.5 MPa. Simulations was performed primarily in the FRACPRO using the numerical model FEFLOW [29].

Table 3

Presentation of selected projects HDR/EGS in progress [1, 2, 3, 8, 17, 18, 25, 29]

Name of the project	Period of activity	Name of the wells	Well depth, [m]	Rock type	Bottomhole temperatures, [^{o}C]	Thermal capacity	Stimulation methods	Model or software
Soultz, France	since1987	GPK-1	3590	Granite	165	1,5 MW_e	Hydraulic fracturing and acidizing	Discrete Fracture Network (DFN); numerical toolbox FRACAS
		GPK-2	5010					
		GPK-3	5100					
		GPK-4	5105					
Groß Schönebeck, Germany	since 2000	EGrSk 3/90	4300	Sandstone and andesitic volcanic rocks	145	10 MW_t*	Hydraulic gel proppant, fracturing, thermal, chemical	Simulation FRACPRO, numerical model FEFLOW
		GtGrSk 4/05	4389					
Landau, Germany	since 2003	Gt La1 Gt La2	3170 to 3300	Granite	159	2 to 5 MW_t	Hydraulic for injector	–
Habanero, Cooper Basin, Australia	since 2003	H01	4421	Granite	242 to 278	1 MW_e	Hydraulic	TOUGH 2
		H02	4459					
		H03	4200					
		H04	4204					
St. Gallen, Switzerland	since 2009	GT-1	4450	Malm, Shell limestone	130 to 150	–	Chemical and hydraulic	–

* Planned thermal capacity

Landau, Germany

The project was initiated in 2003. This is the first geothermal CHP plant in Germany, which is connected to the grid. Project is localized in the Upper Rhine Graben. Uses granite at a depth of 3300 m. Bottomhole temperatures were about 160^oC. For the production well were not performed stimulation treatments. In the injection well chemical method was used. The distance between boreholes is 1.5 km. In Landau was built Organic Rankine Cycle power plant of installed electrical capacity up to 3.6 MW_e and thermal capacity 2 to 5 MW_t [1, 30].

In 2009 was seismic events, which resulted to the temporary suspension of the operations. The works were resumed after purchasing of annual liability insurance to cover potential seismic damages. As a result of these events it was decided to reduce water injection pressure which is strictly related with a reduction in the production of energy. This problem can be solved by using a side-leg concept. This concept allows for distribution of pressure fluid is being introduced on two separate ends, thus minimizing risk of seismic activity. This method was used in previous installations [1, 3].

Habanero, Cooper Basin, Australia

Geothermal project was created in 2003. Rock mass at a depth of about 4200 m formed granites. The project includes 4 wells: Habanero 1 (H01), Habanero 2 (H02), Habanero 3 (H03) and Habanero 4 (H04). To reservoir simulation used software TOUGH 2. This is the first EGS system in Australia generating electricity [1, 10, 17].

The first borehole Habanero 1 drilled in 2003. The well was completed with a 6" open hole section in the granite and 4½" tubing. The first stimulation took place from November to December 2003. Habanero 2 was drilled in 2004. In this borehole occurred complications during drilling process. Habanero 3 was drilled in 2008 and successfully completed with a pre-drilled liner hung across an 8 ½ inch open hole granite section and a short 7 inch kill string. Habanero 4 was drilled in. Completed with an 8 ½ inch open hole granite section and 7 inch tubing [9].

St. Gallen, Switzerland

Project started in 2009. Is located in the north-eastern part of Switzerland in the urban area of St. Gallen. The location EGS system is perfect because heat from geothermal energy for central heating can not be transported over long distances. Drilling process in the project St. Gallen started in 2013 [1, 19]. Details of this and the previously geothermal projects presented in Table 3.

Other present HDR/EGS projects described Breede [1] and Hirschberg [8]. These are: Le Mayet in France, Genesys Hannover in Germany, Newberry in USA, Insheim in Germany, Bruchsal in Germany, Unterhaching in Germany, Neustadt-Glewe in Germany, Desert Peak in USA, Coso in USA. Because the research is in progress the projects are not described in sufficient detail [1, 8].

4. HYDRAULIC FRACTURING

Hydraulic fracturing is a procedure for stimulation permeability of rocks. It is to initiate cracks in the rock mass. The slots are created using injected fluid under pressure into the borehole [13].

One of the models describing the fracturing pressure is Crittendon formula [16]:

$$p_s = K \cdot p_g \tag{1}$$

and

$$p_g = H \cdot \gamma_z \tag{2}$$

and

$$K = \frac{1}{2} \cdot \left[\left(1 + \frac{2m}{1-m} \right) + \left(1 - \frac{2m}{1-m} \right) \cdot \cos 2\varphi \right] \tag{3}$$

where:

- p_s – fracturing pressure [Pa],
- p_g – rock mass pressure [Pa],
- H – depth [m],
- γ_z – specific weight [N/m^3],
- m – Poisson's ratio,
- K – Crittendon's ratio,
- φ – inclination angle of slot.

Value of fracturing pressure is dependent on many parameters. The biggest impact on fracturing pressure is kind of reservoir rocks and their strength properties. An important element is porosity and depth at which we want to fracturing of the rock mass [16].

In view of the growing use of fracturing in geothermal systems HDR/EGS and oil industry has been a lot of progress in techniques and technologies of their realization. Chemical additives for fracturing fluids are safe for the environment. Software programs are developed. It is possible to perform simulations to the best selection designed technological parameters such as injection pressure, rheological properties, fluid flow rate etc.

Fracturing consists of three steps. During the first phase slots are opening (pad) by injection of the fracturing fluid. The next step is to adding proppant with different granularity for supporting slots (proppant stages). In HDR/EGS systems this step is not always implemented. Third step is the flushing wells (displacement) in order to clean it from the proppant, which should only be in the slots [13].

One of the most important topic from the viewpoint of the correct operation of geothermal systems is selection of materials, from which will be prepared drilling casing. Appropriate selection should result in a significant reduction and elimination negative events occurring in the process of operation and their consequences. Designer should take into account primarily the mechanical strength of materials, their vitality, chemical and thermal resistance. Most often material used for casing construction is a steel with high strength.

Often in steel casing is used internal protective coating. It aims is to reduce corrosion and improve the hydraulic properties of geothermal installations. Rarely used fiberglass tubes for strength reasons [11].

5. FRACTURING PRESSURE

The surface fracturing pressure in given formation can be calculated from equation:

$$p_{sf} = p_{bd} - p_h + \Delta p_{wf} + \Delta p_{pf} \tag{4}$$

where:

- p_{sf} – surface fracturing pressure [Pa],
- p_{bd} – breakdown pressure [Pa],
- p_h – hydrostatic pressure in the wellbore [Pa],
- Δp_{wf} – frictional pressure drop in wellbore [Pa],
- Δp_{pf} – frictional pressure drop in perforation [Pa].

The minimum value of breakdown pressure can be found from:

$$p_{bd} = \frac{3\sigma_h - \sigma_H + T_0 - 2\eta p_p}{2(1-\eta)} \tag{5}$$

and

$$\eta = \frac{\alpha(1-2\nu)}{2(1-\nu)} \tag{6}$$

where:

- ν – Poison's ratio,
- H – true vertical depth of the formation [m],
- g – acceleration of gravity [m/s^2],
- α – Biot's poroelastic constant,
- p_p – pore pressure [Pa],
- σ_h – minimum horizontal stress [Pa],
- σ_H – maximum horizontal stress [Pa],
- T_0 – rock tensile strength [Pa].

Hydrostatic pressure in the wellbore is calculated from:

$$\Delta p_h = \rho_f \cdot g \cdot H \tag{7}$$

where:

- Δp_h – hydrostatic pressure in the wellbore [Pa],
- ρ_f – fracturing fluid den sity [kg/m^3],
- H – true vertical depth of the formation [m],
- g – acceleration of gravity [m/s^2].

Assuming uniform stress field in granite, overburden gradient – 25 kPa/m, Poison's ratio – 0.25 and rock tensile strength – 4800 kPa surface fracturing pressure for 5000 m depth formation will have minimum value 62 MPa and for 4000 m depth 51.4 MPa.

The upper limit of breakdown pressure can be found from:

$$P_{bd} = 3\sigma_h - \sigma_H + T_0 - p_p \quad \text{[MPa]} \tag{8}$$

For the same assumptions as in case of lower limit of breakdown pressure, surface fracturing pressure obtain a value of 84.1 MPa at 5000 m depth and respectively 69.2 MPa at 4000 m.

6. CONCLUSIONS

1. In the world is carried out more and more, both geothermal systems HDR as well as EGS. Also issued is numerous publications on them. Despite this, there are many inconsistencies and uncertainties regarding their actions and the consequences of this activity. Questions also concern the possibility of using this form of energy.
2. The main problems are the theme related to the transmission of energy from geothermal systems and effects of stimulation treatments (related with seismic activity). Important issue is the innovation of technology, allowing for exploitation of geothermal resources in an easy and environmentally friendly way.
3. HDR/EGS systems still are in the research and development phase. After eliminating the negative elements HDR/EGS systems have a chance to become one of the best and most promising solutions for use the energy from the Earth's crust.

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