

Drilling Deep Geothermal Reservoirs: the Future of Oil and Gas Business

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Abstract

Most geothermal wells are designed following the same principles as those used in the oil and gas industry, but one-to-one technology transfer has not been fully achieved.

A simple comparison between wells used for geothermal applications with those for oil or gas production shows that the former need to be larger bore, deeper and be in operation for longer time. This paper summarises the main characteristics of HDR/EGS geothermal wells drilled in Germany as well as worldwide experience and compares them with selected oil and gas wells. It illustrates how a more efficient technology transfer from the oil and gas sector can help reduce the cost of geothermal wells.

1. Introduction

Increasing demand for sustainable renewable energy has led geothermal resources to be viewed as a key independent source of energy. In contrast with hydrocarbon developments, geothermal projects require decades of operation before economic payback is achieved from the sale of heat and electricity.

The oil and gas industry has developed highly technical solutions for the exploitation of hydrocarbon reservoirs, especially in the area of drilling, so that operators can safely reach the reservoir target at an acceptable cost, while meeting environmental constraints. These solution must be adapted for the geothermal applications as a function of the geothermal resource.

The main geothermal resources are:

- Hot Dry Rock (HDR), which uses the extremely high temperatures found in rocks a few km below surface. High pressure water is pumped down a well into the hot formation. The injected water travels through fractures in the rock, gets heated up by the rock and travels back to surface via a second well. At surface, the recovered hot water is converted into electricity. Once cooled, the water is injected back into the formation and the cycle is repeated.
- Hydrothermal, which consists of a geothermal reservoir that transfers heat energy upward by vertical circulation of fluids driven by differences in fluid density, corresponding to differences in temperature (NREL, 2006). Hydrothermal resources are the most widely exploited.
- Geo-pressured, which consists of deeply buried reservoirs containing hot brine with dissolved methane under abnormally high pressure (NREL, 2006).

Of the above geothermal resources, HDR is the most challenging from the completions standpoint and also presents the largest project development cost due to depth of the wells. HDR has some major advantages over the other geothermal energy sources. For example, it is environmentally friendly as there is no contamination of the formation fluids and it is widely applicable as it is not limited to active geothermal zones. On the other hand, the main limitation of HDR is the high cost of drilling and completions associated with the greater depths involved. Figure 1 shows the geothermal temperature gradient for selected world regions, with an average of 3 °C/100m. As standard

electricity generation requires temperatures in excess of 180 °C, the depth range for an economic HDR project can be inferred from Figure 1. According to Grimsson (2007), the temperature at depths of 4-5 km can range between 200-300°C in Europe, 300-400°C in the USA and be greater than 500°C in Japan.

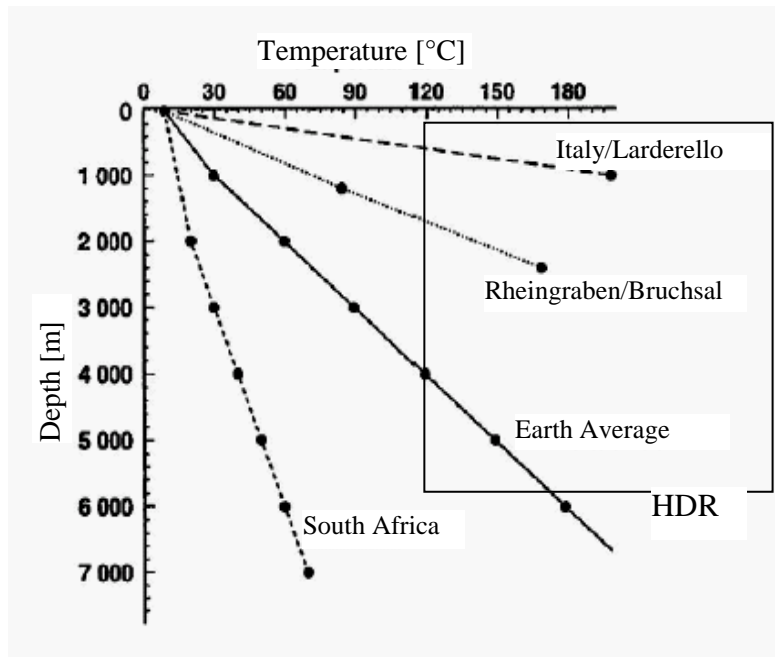


Figure 1. The Earth's temperature gradient, modified after Rogge (2004)

NCDPPEA (2006) presented an economic comparison between the costs of HDR and hydrothermal projects, as shown in Figure 2. The author suggested that the point of minimum costs for a typical HDR project is likely to be encountered later than for a typical hydrothermal project. At some point in time, the cost curves intersect, indicating that, from that point onwards, it becomes less expensive to develop HDR resources than the remaining low-quality/low-enthalpy hydrothermal resources. The same author also estimated that the minimum cost for a typical HDR can be approximately twice that for a hydrothermal project and it will occur after 15 to 20 years.

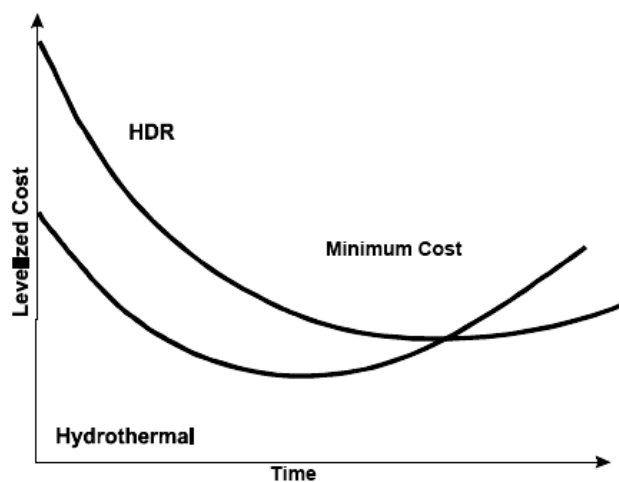


Figure 2. Hypothetical minimum cost curves for hydrothermal and HDR projects, after NCDPPEA (2006)

The costs involved with HDR technology are significant due to the need for two wells, which are usually deviated. Newer concepts such as the Genesys Project, Orzol (2006) propose the use of a single well for both production and injection. Hydraulic fracturing is required to ensure a maximum contact area between heat transport substance (water) and heated formation. The completions of HDR wells are extremely demanding, due to the great depths involved, the high pressure imposed on the well during fracturing operations, the need for an intermediate casing to touch the target, the high temperature at depth and the large temperature variations along the well.

This paper summarises the main characteristics of geothermal wells drilled in various geothermal projects worldwide and Germany and compares them with selected oil and gas wells. It illustrates how a more efficient technology transfer from the oil and gas sector can help reduce the cost of geothermal wells.

2. An overview of worldwide HDR and EGS projects

What follows is a review of some major Enhanced Geothermal System (EGS) projects around the globe. These are engineered systems that can emulate the productivity of viable hydrothermal systems. They include HDR projects as well.

The following major lessons that were obtained from the Fenton Hill project are (MIT, 2006):

- It is possible to create deep (5 km) and high-temperature wells in abrasive, hard rock
- Artificial hydraulically fractures can be generated through stimulation of low permeability crystalline rock
- The EGS reservoir can be circulated for extended time periods and used to generate electricity.
- Creating the connection between wells was a crucial step in developing the EGS reservoir.

The Soultz project is the biggest European project and shows that large fractured volumes can be repeatedly generated in hard and abrasive rock. The work done at Soultz demonstrated that no large overpressures were required to extend the reservoir in order to enhance productivity. Also, the EGS at Soultz was dominated by the natural connectivity of existing fractures, which tell us that drilling techniques must be enhanced in order to drill through highly fractured formations.

The Cooper Basin project in Australia shows that granite can be easily drilled if good drilling practice is applied. It also shows that underbalanced technology should be adopted when drilling through fractured zones.

The Basel project, although uncertain at this time, shows that conventional drilling rigs can be used in urban areas. It also shows that stimulation of crystalline formations may trigger seismic activity, which can have a detrimental impact on society and environment.

The Genesys project, the first of its kind, will show if double wells are essential for EGS systems. It is also based on using a new type of drilling rig specifically designed for urban applications. The success of this project will influence the future of EGS. The concept assumes that although the overall permeability of tight sedimentary formations is low, open flow paths (faults, fracture zones, or intersections of them) exist at great depths and that these paths can be accessed from one borehole by creating extremely large hydraulic fractures (Orzol et al. 2005). The hot water produced from these features will be re-injected after use via the annulus of the same borehole into a permeable rock formation at more shallow depths.

Table 1. An overview of worldwide HDR and EGS projects, after Evans (2005) and Haering (2007)

Project Location	Time	Target Depth	Temperature
Fenton Hill, New Mexico, USA	1972-1996	2.8 to 4.2 km	320°C
Rosenmaqnowes, Cornwall, UK	1978-1991	2.0 km	85°C
Hijiori, Japan	1985 – 2002	1.8 to 2.2 km	270°C
Soultz, France	1987-present	3.3 to 5.0 km	200°C
Ogachi, Japan	1989-2001	0.7 to 1.0 km	250°C
Cooper Basin, Australia	2003-present	4.2 km	240°C
Bad Urach, Germany	1989-1994 (2002-2004)	4.5 km	170°C
Groß Schönebeck, Germany	2002-present	4.4 km	150°C
Otterbach 2, Swiss	2001	2.8 km	120°C
Basel, Swiss	2000-present	5.0 km	~200°C
Genesys Hanover, Germany	2008-present	4.2 km	~ 130°C

3. A comparison of geothermal well completions

Based on the available literature, a comprehensive comparison of geothermal well completions is presented as follows.

The diameter of the last casing string in a geothermal well, often termed the production casing, is commonly 9–5/8” (244mm) (Teodoriu, 2005). Such a large diameter pipe requires a correspondingly larger surface casing and a 13–3/8” (340mm) diameter is commonplace in the USA and Japan (Bohm, 2000; Jotaki, 2000; Williamson et al., 2001). Any well drilled deeper than 3 km would present temperatures in line with those typical of higher enthalpy geothermal resources (Tenzer, 2001). In Europe, the majority of the geothermal wells which have been drilled to depths greater than 4000m are completed with surface casing diameters of 18–5/8” (473mm) or greater (Tenzer, 2001). The large diameter of production casings is a consequence of the amount of fluids that needs to be produced from geothermal wells. For large installed power systems, production diameters of 13–3/8” (340mm) are required, but such diameter requirements strongly affect well costs.

An overview of solutions adopted for geothermal well planning and casing design shows that the actual geothermal approach remains based on old oil and gas solutions. For example, a short review of casing grades and connections used for geothermal wells reveals that:

- The following casing grades have been reported as commonly used in geothermal applications: J-55 (Brunetti and Mezzetti, 1970; Carden *et al.*, 1983; Chiotis and Vrellis, 1995), usually replaced by K-55 for deep applications; N-80 (Brunetti and Mezzetti, 1970; Ragnars and Benediktsson, 1981; Carden et al, 1983; Chiotis and Vrellis, 1995; Witcher, 2001), usually replaced by L-80 in the presence of H₂S (Lazzarotto and Sabatelli, 2005); C-95, which has recently been replaced by T-95, though some authors also report S-95 (Carden *et al.*, 1983) and rarely P-110, in the absence of H₂S. For extreme environments, 9

Chrome L-80 and 13 Chrome L-80 can be utilized. Despite the often prohibitive costs, titanium (Beta-C Titanium) has been used for severe conditions (Pye *et al.*, 1989).

- The following casing thread types are used in geothermal well completions: API Round (Brunetti and Mezzetti, 1970; Ragnars and Benediktsson, 1981; Chiotis and Vrellis, 1995), virtually discontinued today; API Buttress (Brunetti and Mezzetti, 1970; Nicholson *et al.*, 1982; Carden *et al.*, 1983; Chiotis and Vrellis, 1995), which is known for its high axial tensional strength, but low compressive strength; premium connections (Carden *et al.*, 1983), which are mostly used for production casing only, due to the associated high costs.
- Casing pre-tensioning is reported by many authors as a common practice for geothermal well completions (Brunetti and Mezzetti, 1970; Carden *et al.*, 1983; Chiotis and Vrellis, 1995).
- Teodoriu and Falcone (2009) showed that for deep geothermal well completions casing fatigue must be considered, especially when long term well integrity becomes important. The results showed that, under extreme loads, the low cycle fatigue resistance of the buttress thread connection can be as low as 10 cycles.

It must be noted that the use of expensive steel grades, which are common for challenging oil and gas wells, may be prohibitively expensive for geothermal wells. As shown above, many geothermal wells are designed using pre-tensioning in order to compensate for thermal expansion. This is a common solution for oil and gas wells exposed to high temperatures, but most of these wells are drilled to low to moderate depths. Pre-tensioned casing strings in deep wells will imply the use of heavy casings with associated economical and installation impact.

4. Technology Transfer Aspects of Geothermal Activities

Many authors have suggested that the key to good well design lies in applying the same principles as those used in oil and gas industry but new concepts are needed in order to further cut down the costs (Reinicke *et al.* 2009, Polsky *et al.* 2009, Falcone, 2008).

In order to achieve a maximum installed power per geothermal well, high flow rates are required. To achieve this aim two options are available: to increase well diameter (production casing) or to drill multiple wells. Depending on well location and drilled formations, either solution may be economic. However, as observed by Teodoriu (2009), there is a preference for increasing well diameter. In this case, EGS poses a dilemma with regards to well design in that to drill deeper with a larger diameter causes costs to escalate dramatically. Additionally, large, high flow rate pumps (line shaft or electrical submersible) must be accommodated in geothermal wells that require external energy to extract the hot water from the reservoir. This is true for binary wells (temperature < 180 °C) and also for deep EGS, where induced flow circulation of an external fluid is necessary. The need for large pumps will alter future geothermal well design. Figure 3 (left) shows a completion diagram for a geothermal producing well requiring pumping, based on the analysis of several geothermal projects worldwide. The setting depth of the 9–5/8" (244mm) casing is calculated so that the downhole pump is completely submerged at maximum flow rate. This depth may vary depending on the characteristics of the specific geothermal reservoir. Figure 3 (right) shows an ideal geothermal well for EGS applications. Other authors (Reinicke *et al.*, 2009) presented the concept of monobore construction using expandable tubulars. The references studied within this paper showed the need to increase wellbore diameter by new well design: monobore (Reinicke *et al.*, 2009), leaner casing

design and use of expendables, (Polsky *et al.*, 2009), single well instead of doubles, (BGR, 2009) and/or reducing drilling costs (Reinicke *et al.*, 2009).

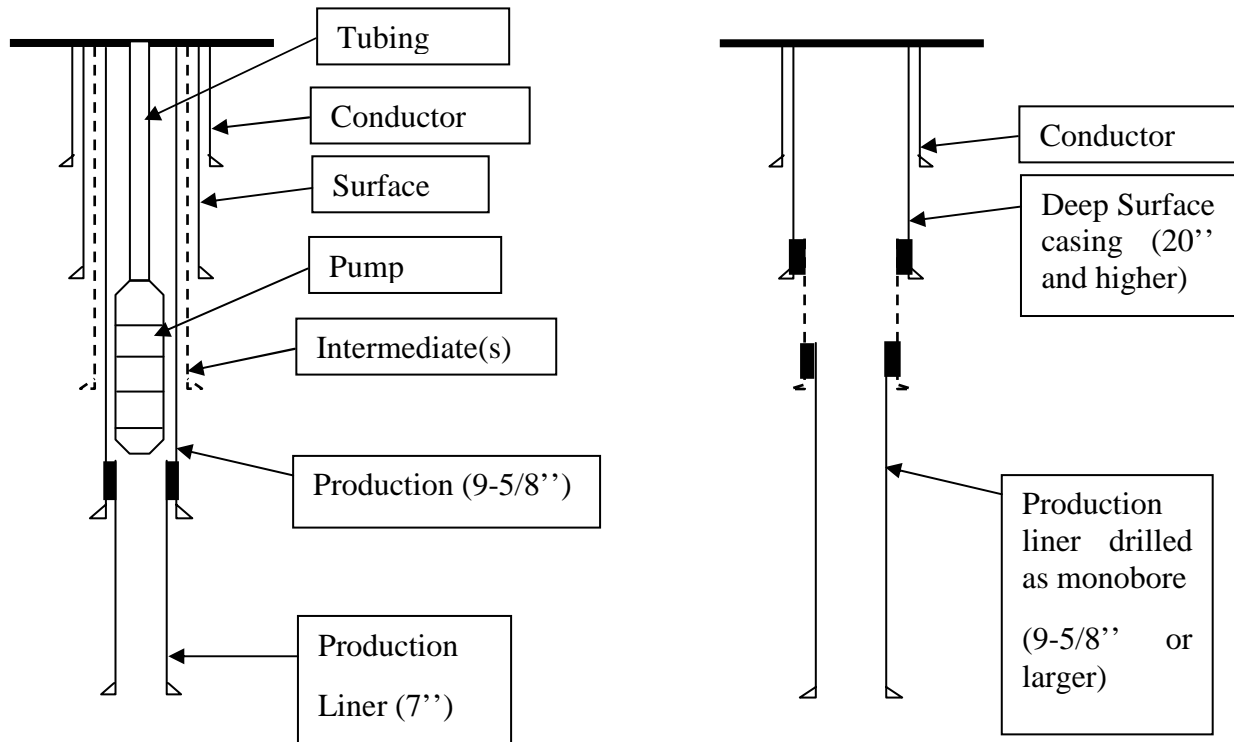


Figure 3. Schematic description of a typical geothermal well (left) and the ideal representation of a well schematic for EGS applications

Polsky *et al.* (2009) presents a synopsis report to evaluate well construction for EGS starting from a synthetic well that shows a production section made of one 7'', one 9-5/8'' and one 13-3/8'' production liner, see Figure 4.

The main challenges for geothermal completions are: the quality and long-term behaviour of the cement, the selection of the appropriate casing hanger (able to withstand high temperatures) and the evaluation of thermally induced loads. Casing fatigue and cement integrity are key issues for geothermal wells since the desired lifetime is higher than for oil and gas. For example, Carden *et al.* (1983) pointed out that despite the continuous casing design improvements, there still remain unknown factors related to casing fatigue and cement integrity that could potentially cause problems in long-term production operations. Teodoriu and Falcone (2009) reports about casing fatigue resistance, pointing out that under extreme cases the casing may withstand only 10 thermal cycles.



Figure 4. The synthetic well presented by Polsky *et al* (2009)

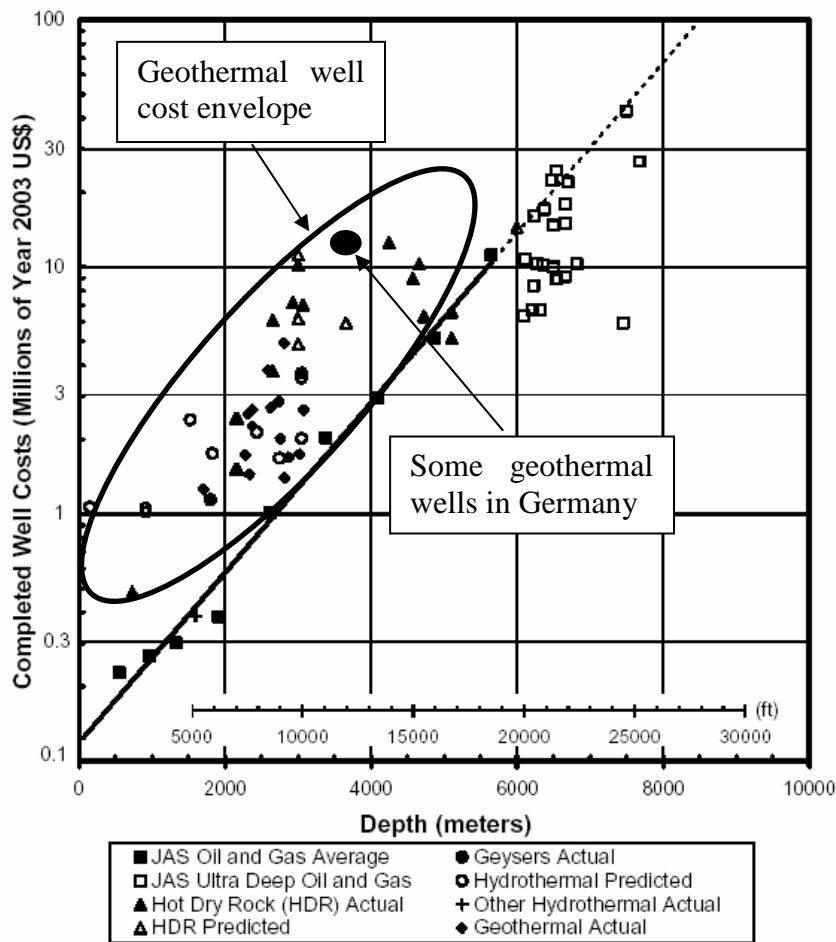
If deep geothermal systems follow the same path as the oil and gas industry, then the drilling and completion costs will inevitably be high. Figure 5 shows a comparison of actual drilling costs for both geothermal and oil and gas applications (Tester *et al.* 2008) and one can observe the classical exponential tendency of drilling costs with depth (linear if logarithmic scale is used). All reported geothermal well costs in Figure 5 are higher than the equivalent oil and gas wells (same depth). Some causes that will generate additional costs to a geothermal well are listed below:

- Drilling in hard formations, which are unlikely to exist as oil and gas reservoir
- Drilling in tectonically “sensitive” areas and through faults
- High temperature environment

In comparison to worldwide experience, the geothermal well costs in Germany are higher than the average. Here we must mention that local geological conditions may generate additional costs for geothermal wells drilled in Germany. Some encountered problems are mentioned as follows:

- drilling problems (stuck pipe issues and mud losses, casing running problems, wellbore instability associated with stuck pipe and casing running, cementation problems, drilling through hard formation)
- risk associated with geothermal reservoir (temperature other than predicted, depth other than predicted)
- stimulation issues (fracture propagation other than predicted)

Since its existence, the oil and gas business is working hard to reduce the drilling costs, but not at a risk to safety or the environment. Therefore, in order to significantly reduce drilling and completion costs for future geothermal wells, new concepts and new technologies must be developed.



1. JAS = *Joint Association Survey on Drilling Costs*.
2. Well costs updated to US\$ (yr. 2003) using index made from 3-year moving average for each depth interval listed in JAS (1976-2003) for onshore, completed US oil and gas wells. A 17% inflation rate was assumed for years pre-1976.
3. Ultra deep well data points for depth greater than 6 km are either individual wells or averages from a small number of wells listed in JAS (1994-2002).
4. "Geothermal Actual" data include some non-US wells (Mansure, 2004)

Figure 5. Drilling costs of oil, gas and geothermal wells, after Tester *et al.* (2008)

Another simple example is presented here to show the effect of heavier casing on drilling rig selection. A hypothetical well is drilled to a depth of 5000m and then cased with a 9-5/8" production casing. The required hook load is calculated based on 5000m of 48.07 KG/M (32.3 LB/FT) casing, which displaces a weight of 240 tons in air. Adding a 25% over-pull capacity to the casing weight leads to a total hook load of 300 tons. If a heavier production casing is used, such as 69.94 KG/M (47 LB/FT), the hook load for the same well with the 25% over-pull capacity would be 437 tons. This example shows that deep wells with inadequate well planning may require rigs with higher specifications, with corresponding higher costs, although the use of liners should reduce the required hook load.

The use of liners for geothermal well construction can also save costs if the well integrity is not compromised. However new solutions are expected to be developed in the near future in order to reduce well costs.

3. Conclusions

With increasing demand for renewable energy, the EGS and its predecessor, the HDR, may close the energy gap. EGS will require deep drilling (beyond 5000 m) and large diameters in order to provide high power output per well.

As of today all reported costs associated with geothermal costs are higher than those for equivalent oil and gas wells.

The future geothermal wells will require larger diameter when compared with oil and gas wells. This will generate higher hook loads for the drilling rigs and associated high drilling costs.

New well construction solutions are required in the near future to allow an economical exploitation of geothermal deep resources.

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