Sustainable Energy Opportunities within the Geothermal Continuum

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ABSTRACT

The publication of “The Future of Geothermal Energy” in 2006, which resulted from a comprehensive assessment of US geothermal potential, brought renewed interest in Engineered Geothermal Systems (EGS) worldwide. The magnitude and accessibility of the geothermal resource within a continuum of grades, coupled with its predicted ability to provide baseload renewable electric power at large scales without carbon emissions, makes it a particularly attractive alternative to fossil-fuel-fired electricity production. Widespread deployment of geothermal energy to meet projected demand growth and to replace aging fossil generation capacity would significantly lower carbon emissions in the US as well as globally. The effects of resource quality, reservoir performance, and drilling technologies on EGS economic feasibility were examined parametrically to identify areas for intensified research and development.

Keywords: geothermal continuum, EGS, carbon reductions, well costs, drilling innovation.

1 CONTEXT

The assessment of the US engineered geothermal systems (EGS) resource was carried out over a 15-month period by an 18-member international panel. Major emphasis was placed on quantifying the geothermal resource regionally and on the EGS technology and economic conditions needed for US large scale deployment of EGS to reach a generating capacity of 100,000 MW_e by 2050 (Tester et al., 2006). Using the methodologies that were applied to the US, estimates of the global impact of EGS can be made as well.

2 RESOURCE POTENTIAL

The geothermal resource can be viewed as a continuum of grades ranging from low-grade, conduction dominated EGS to high-grade, hydrothermal resources. Resource grade depends on average temperature gradient (rock temperature vs. depth), natural connectivity and fluid content. High-grade resources have a high temperature gradient, high natural connectivity and high fluid content while low-grade resources have a low temperature gradient, little or no natural connectivity and little or no fluid content. A depiction of the continuum can be seen in Figure 1.

Figure 2 shows the available world and US geothermal resource. All estimates are shown in exajoules (EJ) or 10^{18} joules. The quality of the resource grade is inversely related to its quantity as is often the case with mineral resources. Given that the bulk of the geothermal resource lies in well-distributed grades of conduction-dominated resources, EGS technology must be developed to an economically feasible stage in order for geothermal energy to have a significant impact on world energy supply.

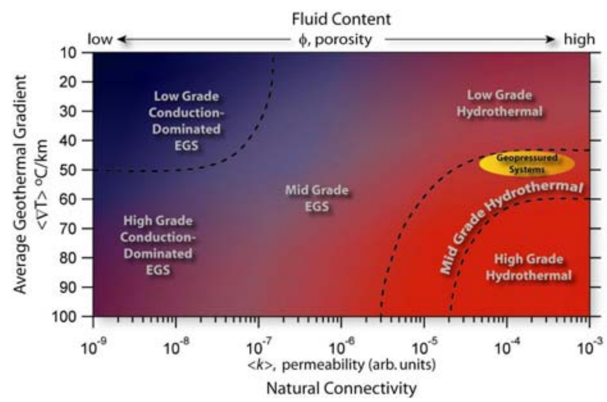

Figure 1 - The continuum of geothermal resources as a function of average temperature gradient, natural connectivity and fluid content (Thorsteinsson et al., 2008)

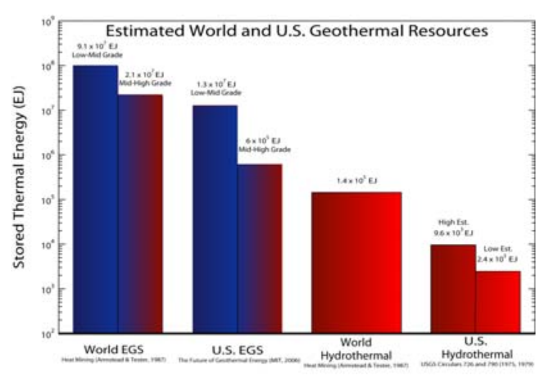

Figure 2 - Energy resource base for different types of geothermal resources. World data: (Armstead & Tester, 1987), US EGS data: (Tester et al., 2006). US Hydrothermal data: (Muffler & Guffanti, 1979).

3 CARBON REDUCTIONS

By deploying EGS generation capacity at a scale of 100 GW_e or larger, significant reductions in carbon emissions from the electrical sector are possible. Based on EIA 2007 data and projections out to 2030 (Energy Information Administration, 2007a), it was estimated that 100 GW_e of EGS capacity online in 2006 would have reduced US CO_2 emissions by 30%, while 100 GW_e online by 2030 would reduce CO_2 emissions by 21%. These estimates assume that EGS replaces only coal and natural gas electricity generation and that the replacement is non preferential and relative to their generation share. Also, for simplification, it was assumed that EGS power plants were emission free binary plants with a capacity factor of 95% (Thorsteinsson et al., 2008).

Developing EGS resources worldwide would reduce greenhouse gas emissions even further. Preliminary calculations were done using EIA emissions data and projections out to 2030 for domestic and worldwide CO_2 emissions from coal and natural gas (Energy Information Administration, 2007b). As a conservative estimate, EIA emissions data for US electricity production were used to calculate the average emissions per kWh of electricity production from coal and natural gas for 2006 and 2030 (Energy Information Administration, 2007a). Carbon reductions per EGS kWh online were calculated by reducing CO_2 emissions by a weighted average of coal and natural gas emissions per kWh based on the fuels' relative share of the US electricity market that year. This gives a replicable base for emission reduction calculations. EGS power plants were assumed to be emission free binary plants with a capacity factor of 95%. These rough calculations provide indications of the effect of wide scale deployment of EGS technology and show that 800 GW_e online in 2006 would have reduced global CO_2 emissions by 33%, while 800 GW_e of EGS capacity online by 2030 would reduce global estimated emissions by 19%.

4 EGS ECONOMIC MODEL

Using an updated version of the MIT EGS model, capital and well costs for geothermal power plants were estimated. The model was originally developed at MIT by Tester and Herzog (Tester & Herzog, 1990) and then enhanced by Anderson for use in the MIT geothermal assessment (Tester et al., 2006).

4.1 Assumptions and Range

A range of depths, production flow rates and temperature gradients were explored to map EGS development costs across a wide range of geothermal resource and reservoir grades while staying within current and anticipated well completion depths. Depths from 3-10 km were analyzed along with average temperature gradients ranging from 10-100°C per km and production well flow rates of 20, 40, 60, 80 and 100 kg/s. An important characteristic of these systems is the inherent coupling between well drilling, reservoir design and stimulation and well production flow rates. For a fixed resource temperature, the number of wells required decreases linearly with increases in reservoir productivity. So at higher flow rates, fewer wells are needed for the same power output. The feasible temperature range for geothermal electricity production was assumed to be 100°C to 400°C. As in the 2006 MIT assessment, stimulation costs were assumed to be $500,000 per well and the same base case financial assumptions were used except for the production to injection well ratio, which was changed from a quartet configuration to five production wells per four injection wells and the debt to equity ratio which was changed from 60/40 to 70/30. All cost figures are cited in 2004 $ unless otherwise noted (Thorsteinsson et al., 2008).

4.2 Surface Plant Costs

In our analysis, we assumed that organic binary power plants would be used to generate electricity from the EGS resource. This is a conservative assumption as binary plant capital costs in $/kW installed are typically higher than those of steam flashing plants for resource temperatures above 200°C. Surface plant costs were estimated using a linear correlation that resulted from the 2006 MIT study:

$$C = 2642.025 - 3.5 * T \quad (1)$$

Where:
C = surface plant capital costs ($/kW in 2004 $)
T = geothermal fluid temperature (°C)

4.3 Drilling Cost Cases

Using the Wellcost Lite model developed by Livesay and co-workers (Mansure et al., 2005), EGS well costs were estimated for three different cases. The base case scenario assumes the same assumptions as the Wellcost Lite model (see chapter 6 in Tester et al, 2006). To analyze the effects of increased flow rates, the base cost case with an increased flow rate from 20 kg/s to 80 kg/s was used. Finally, an advanced drilling cost scenario with the same increased flow rates was examined. The advanced case assumes technology innovations that eliminate the need for intermediate casing intervals, allowing for "single-diameter" wells and thus reduced drilling costs. Furthermore, it assumes drilling innovation that allows for wells to be drilled continuously by eliminating the need for drill bit replacement, which reduces tripping and drilling times and thus reduces costs even further. Finally, advanced casing methods that utilize lower cost materials than the casing methods currently employed were added. The effect of these innovations on drilling costs within the framework of conventional drilling practices was projected (Thorsteinsson et al., 2008).

5 MODEL RESULTS

The model shows that well costs are a dominant cost factor in current EGS projects (see Figure 3). With today's drilling technology and production flow rates, drilling completion costs represent about 90% of the total costs of an EGS project in a high-grade EGS resource area, i.e. a conduction dominated area with average temperature gradients between 70-100°C/km. With increased production flow rates, the number of wells required decreases and the associated well costs drop down to about 70% of the total cost. With innovation in drilling technology resulting in lower costs, the percentage decreases to 45% and consequently well costs are no longer the most significant barrier to EGS development.

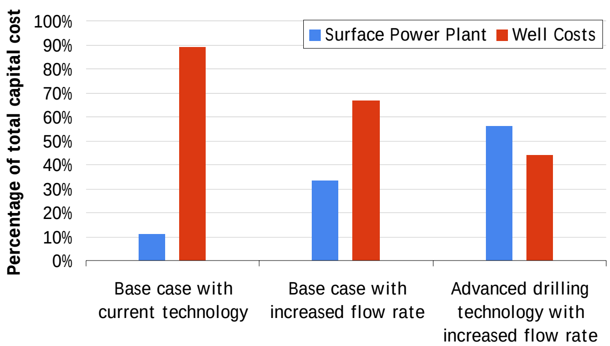

Figure 3 - High-grade EGS (70-100 °C/km). Surface plant and well costs as percentage of total costs

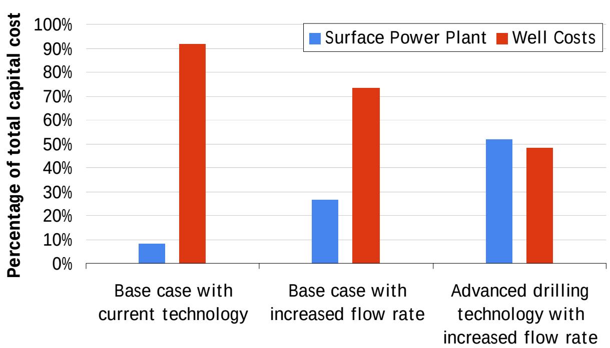

Figure 4 - Mid-Grade EGS (40-70°C/km). Surface plant and well costs as percentage of total costs

For mid-grade EGS resources, i.e. conduction dominated areas with an average temperature gradient of 40-70°C/km, well costs are even more dominant. Using today's drilling technology and stimulation success, drilling completion costs would represent about 90% of total costs for an EGS project in a mid-grade EGS resource area. As production flow rates increase that percentage goes down to about 70% and with innovation in drilling technology can go as low as about 50% (see Figure 4).

For low-grade EGS resource areas, or conduction dominated areas with average temperature gradients of below 40°C/km, well costs are an even greater barrier for development. Based on current technology, drilling completion costs would represent 98% of total project costs for an EGS project in a low-grade resource area. With a fourfold increase in production flow rates, that percentage is lowered to 91%, but it is not until significant innovation in drilling technology is achieved that that drilling cost portion can be lowered substantially to 72% of total project cost (see Figure 5).

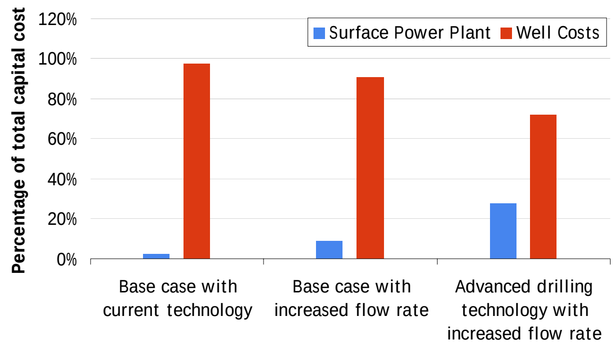

Figure 5 - Low-grade EGS (<40°C/km). Surface plant and well costs as percentage of total costs

6 EGS TECHNOLOGY INNOVATION

The dominance of drilling costs in EGS projects, especially in mid- to low-grade resource areas which represent the largest and most well distributed fraction of the EGS resource nationally, highlights the importance of developing both reservoir stimulation techniques and new, lower cost drilling technologies.

6.1 Reservoir stimulation improvement

The EU sponsored EGS field experiments in Soultz, France reached sustained production flow rates of 25 kg/s (Baria & Petty, 2008). A rate of 20 kg/s was used as a base case rate for this paper. The project developers in Soultz, at Copper Basin in Australia, and elsewhere have clear plans to increase production flow rates two to four fold to 40 to 80 kg/s per production well which will greatly enhance the economic feasibility of EGS (Tester et al., 2006).

6.2 Drilling technology innovation

Drilling technologies are constantly evolving and improving. Despite these advances, the principles behind conventional rotary drilling have remained essentially unchanged for the past 100 years. In order to dramatically decrease costs associated with drilling in the near term, disruptive technologies that change the fundamental cutting mechanism are needed. Examples of novel drilling techniques that hold promise include chemical dissolution (Polizzotti et al., 2003), particle impact (Geddes & Curlett., 2006) and thermal spallation or fusion (Potter & Tester, 1998). The latter is of particular interest to the authors and

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is currently under development in our laboratories at MIT and at ETH Zurich.

Thermal spallation is the fragmentation of a brittle solid into disc-like flakes (spalls) caused by rapidly heating a confined rock surface. Rapid heating induces large thermal stresses in the rock that lead to the formation and violent ejection of spalls from the surface. Hard polycrystalline rocks which are difficult to drill economically by means of conventional drilling methods can often be easily spalled thermally. However, more research is required to determine the practical feasibility of a thermal spallation process for use in drilling deep boreholes at depths of several kilometers. If the formation is resistant to spallation then rock melting using the same heat source would provide an alternative means of penetration. High hydrostatic pressures are induced by drilling fluids that are used in the deep well bore drilling process. Consequently our research is focused on the characterization of flame jets in high density water at supercritical water pressures up to 300 bar to simulate drilling at depths in excess of 2 km. Ongoing research at MIT and ETH Zurich make use of prototype flame reactors to simulate conditions downhole and address important scientific questions concerning the thermal spallation process (see Figure 6) (Wellig et al., 2005).

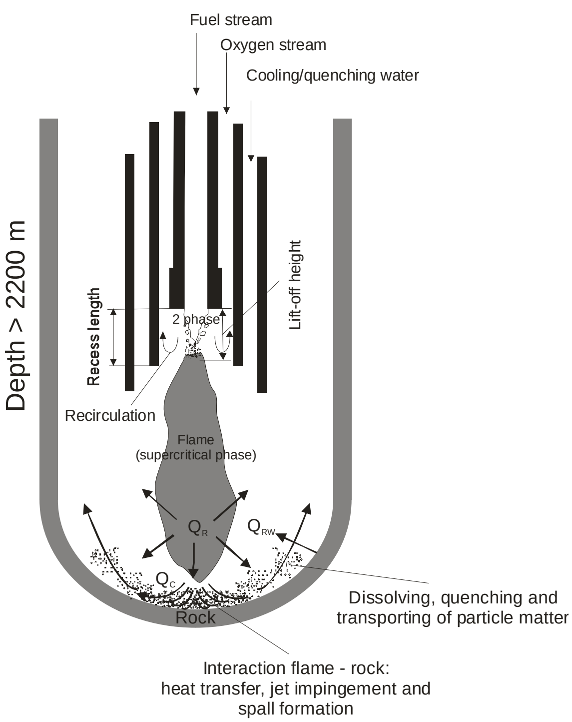

Figure 6 Thermal spallation process depicted schematically using hydrothermal flames in high pressure water in a deep borehole

Projects involve the theoretical modeling and experimental investigation of producing sufficiently high temperatures and heat fluxes from flames in high pressure water to induce thermal spallation in rock samples. Current testing is focused on producing stable free flame jets at supercrticial pressures, and testing the effect of a variety of nozzle and burner configurations on flame ignition and stability. Optimization of the flame jet heat flux to the rock surface and thermal spallation feasibility experiments with differing rock types are underway. It is hoped that this research will lead to a commercially viable drilling system that will dramatically reduce the costs associated with drilling through hard, crystalline rocks to depths approaching 10 km.

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