ENVISIONING A MODEL FOR INNOVATIVE EGS DEVELOPMENT IN THE SAN FRANCISCO BAY AREA

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INTRODUCTION

Expansion of Enhanced Geothermal Systems (EGS) in the United States is stinted primarily by the high cost associated with several stages of development, most notably drilling (Figure 1). However, thorough research and costing of advanced EGS techniques predict a significant cost reduction through use of innovative methods. The aim of this report is to provide a model, based on the specific geology of the San Francisco Bay Area, for implementation of some of these technologies that have not yet been applied in industry, but could be the key to EGS becoming economically feasible on a large scale.

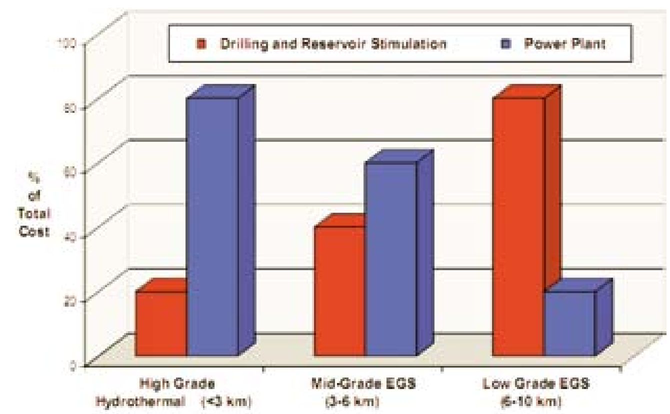


Figure 1. High Cost of Drilling at Depth (Tester, 2011).

SITE SELECTION

The San Francisco Bay Area was chosen as a general target for this project for the following reasons:

1. The presence of many active fault zones results in a higher temperature gradient.
2. The mild climate will facilitate drilling and construction and eliminate concerns of freezing in the condenser or other weather-related failures.
3. The high population density will allow for more efficient power transmission to a greater number of households.
4. The region is a cultural and political epicenter for development of sustainable technologies, so an EGS project here would be an opportunity to garner influential public support.

In order to further narrow down the site of the project, Google Earth heat and fault maps were examined to identify hot spots of increased seismicity. One such area is the Hayward Fault, which is very active and thus creates a high temperature gradient in the surrounding area. The region to the east of the city of Hayward was selected as the site for drilling. Additional benefits of this site are the close proximity to San Francisco (high population density and demand for power), the existence of undeveloped land to the east of the fault, and the network of highways and roads that will allow easy access to the site. Figure 2 and Table 1 show the important geological characteristics of the site, compiled from Google Earth and USGS.

Figure 2. Temperature at 6.5 km depth near the Hayward Fault Line (Hayward, CA, 2012).

Table 1. Geological Characteristics of the Area.

Temperature Gradient	30°C/km
Surface Heat Flow	85 mW/m^2
Mineralogy	Miocene/Cretaceous Marine Rocks (sandstone, mudstone, shale; basement at depth low porosity, high hardness
Seismicity	Hayward Fault Line

The following subsequent steps should be taken to complete geological exploration and secure the site:

- Gain a better understanding of the fault zone and the potential for induced seismicity by using a program such as LiDAR that can create Digital Elevation Models (DEMs).
- Determine the borders of parkland and protected areas in the undeveloped region.
- Complete the permitting process.
- Gain the support of the local population through open communication and additional safety measures
- Drill exploration wells to verify the temperature gradient, and obtain core samples.
- Conduct various geophysical exploration tests (gravity, magnetic, electric resistivity, etc) as deemed necessary.

DRILLING

The well goals are shown in Table 2.

Table 2. Well Goals

Target Depth	6.5 km
Bottom Hole Temperature	225°C (Hayward, CA 2012)
Mass Flow Rater Per Well	75 kg/s
Number of Production Wells	≥ 5-6 (DiPippo 2012)
Number of Injection Wells	≥ 2-3 (DiPippo 2012)

Production Wells

The best way to achieve an optimally productive geothermal resource would be to directionally drill across the Hayward Fault, as the fault itself will likely have higher temperatures and flow rates than the surrounding impermeable rock. If the fault cannot be drilled into directly, an alternative approach would be to stimulate and produce from the micro-fractures surrounding the fault.

Injection Wells

Injecting back into the Hayward Fault would not be desirable, as this would allow almost immediate communication between the injection and production wells. Therefore, the best approach is to inject into the micro-fractures surrounding the fault so the cool fluid can filter slowly back through the fractures and reheat before reaching the fault. DEM should be used to find microfractures, as well as to model stimulation and enhancing of the fractures and flow of the injection fluid.

INNOVATIVE METHODOLOGIES

Achievement of the following three objectives will most significantly reduce the cost of deep drilling (Thorsteinsson et al., 2008)(Figure 3).

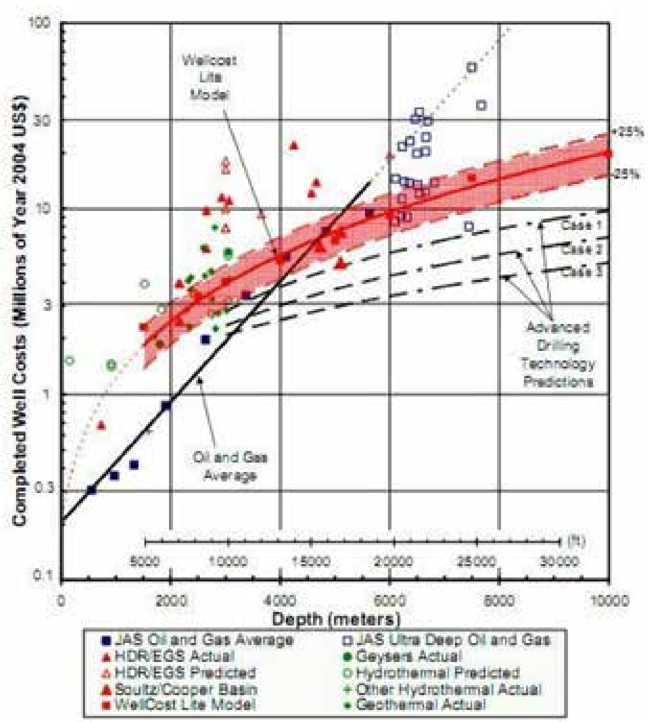


Figure 3. Well cost vs depth for three cases described above (Thorsteinsson et al., 2008).

- **Objective 1: Single Diameter (Monobore) Well**
  - **Solution 1: Open Hole Drilling.** Deep wells in hard rock, such as the granite found on this site, can often be drilled as open holes over long distances, as was done at the Fenton Hill site (Thorsteinsson et al., 2008).
  - **Solution 2: Expandable Tubular System.** An expandable tubular system allows the casing and liner to be extended into the wellbore in a telescoping manner, and to later be expanded downhole.
- **Objective 2: Continuous Drilling**
  - **Solution: Hydrothermal Spallation.** In this drilling method, a downhole burner applies a high heat flux, thereby inducing stress and causing the rock to split into spalls (Figure 4). The spalls are then washed out of the wellbore by the drilling fluid. Potter Drilling estimates that hydrothermal spallation will cut back on drilling costs and time by 15-20% (Potter, 2010), largely because of the reduction in trips due to the lack of a bit. In addition, hydrothermal spallation is very efficient in granite, with a rate of penatration of 30 ft/hr which stays consistent down to a depth of about 9 km (Potter, 2010). It is also compatible with a coiled tube drill rig, which would allow electricity to be transmitted downhole for the purposes of using active downhole steering tools and collecting real-time downhole data (Sandia, 1996). Finally, hydrothermal spallation can be used for high angle directional drilling in hard rock (Potter, 2010). The combination of all of the above benefits will greatly increase the chance of accurately drilling to the target.

Figure 4: Hydrothermal Spallation (Potter Drilling, 2012).

- **Objective 3: Reduced Casing Costs**
  - **Solution: Incorporated in the above solutions**

Fracturing

Assuming that drilling proceeds successfully and reaches the micro-fractures around the fault, the method selected for enhancing the fractures will be hydroshearing (Figure 5). This method, developed by Altarock Energy, hydraulically stimulates existing fractures by injecting high-pressure water, which lowers friction and allows the fracture walls to slip, thereby opening the fracture. It requires a lower water pressure than hydraulic fracturing, and it is also more effective in hard, impermeable rock (Altarock Energy, 2012). The Newberry EGS demonstration project currently being developed by Altarock will be the first test case in the field for hydroshearing.

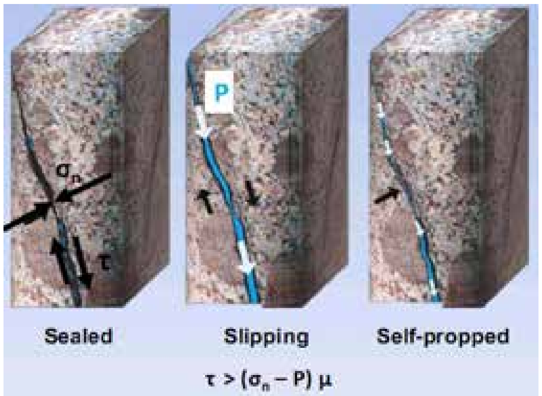


Figure 5. Hydroshearing (Altarock Energy 2012).

The following measures should be taken in conjunction with hydroshearing:

1. **Water:** The water required for hydroshearing and reinjection should be sourced from co-production from oil and gas wells, and from municipal waste water, as much as possible.
2. **Diverters:** The Altarock Newberry EGS demonstration project will use a diverter called TZIM (thermally degradable zonal isolation material). The purpose of a diverter is to plug up existing fractures to divert the pressured water to new fractures, thus allowing each well to access multiple fractures and increasing the mass flow rate. Assuming that this method will create 3 fractures accessible from each well, the expected mass flow rate can be tripled from 25 kg/s to 75 kg/s. TZIM is also non-toxic, thermally degrading, and environmentally safe (Altarock Energy, 2012).
3. **Tracers:** Tracer tests should be used to ensure that the production and injection wells have an optimal level of connecvitivity.
4. **Seismic Monitoring:** Seismicity in the region should be heavily monitored through the installation of a microseismic array. Additionally, following the example of the Newberry EGS demonstration project, an ISMP (induced seismicity mitigation plan) should be written and made publicly available in order to establish a better relationship with the local population.

POWER PLANT

The base power plant initially installed for this site should be a simple single-flash steam power plant. This type of plant is generally the first system installed at a liquid-dominated geothermal field. Additionally, for an EGS reservoir at 225°C, single flash is the optimal system (DiPippo, 2012). The main disadvantage of this system is that the use of a water-cooling system results in a very low reinjection rate. However, if the make-up water for reinjection is drawn from co-produced water from oil and gas wells as well as municipal water, the impact on the environment will be lowered significantly.

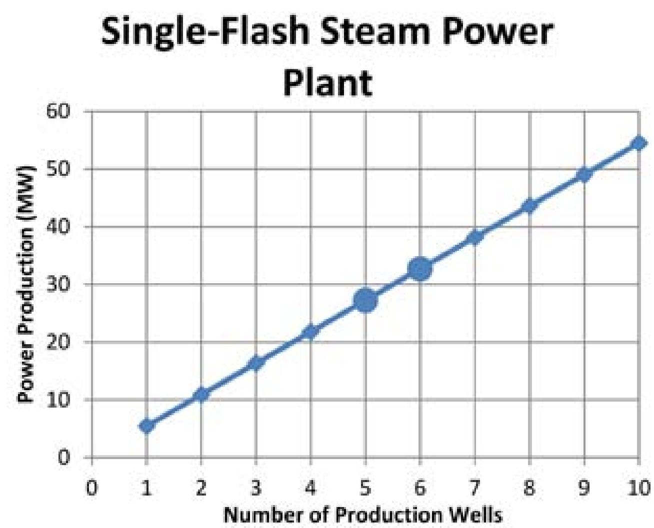
Calculations based on the previously-stated well characteristics result in the following specifications for the power plant:

- Condenser Temperature = 50°C
- Separator Temperature = 137.5°C

Additionally, Figure 6 shows the predicted power output of the plant as a function of the number of production wells.

Figure 6: Power plant output vs. production wells

If the single-flash plant is operated successfully for a significant amount of time, the system may be evaluated for the potential to add on more advanced power plant components and cycles that would increase the power output. The following options should be considered:



- Integrated Single- and Double-Flash
- Integrated Flash-Binary
- Solar-Augmented Flash

COSTING AND CONCLUSIONS

Table 3 shows the result of calculations for a choice of 5 production wells, 2 injection wells, and a 27 MW power plant.

As can be seen in Table 3 employing innovative drilling technologies as implemented in this model successfully reduces drilling costs from 60 to 70% of total costs, as seen in Figure 1, to 25 to 30%, which more closely matches the ratios seen in projects at shallow depths.

Although 5 to 6 production wells and 2 to 3 injection wells is the recommended starting point for the project, the developer may choose any number of wells deemed to be most profitable. The graph below shows the net yearly profit as a function of the number of years of plant operation for a range of production wells (Figure 7).

In the range of 4 to 10 production wells, the payback time is 3 to 4 years, a figure which is not just economically feasible, but better than average in the geothermal industry.

Table 3. Result of calculations for a choice of five production wells, two injection wells, and a 27 MW power plant.

Initial Project Costs:	
Exploration and Site-Related Costs	$22,013,152.21
Drilling Costs	$25,200,000.00
Fracture Enhancement	$915,652.25
Power Plant	$41,689,391.04
Government Grants and Private Investments	- $24,000,000.00
TOTAL INITIAL COST	**$65,818,195.50**
Yearly Project Costs:	
O&M	$4,057,767.39
Royalties/Taxes	$527,509.76
TOTAL YEARLY COST	$4,585,277.16
Yearly Earnings:	
Price of Electricity in CA	12.6 ¢/kWh
Power Plant Production	27.247968 MW
YEARLY EARNINGS	**$30,075,217.16**
Net Discounted Profit	
Year	Net Profit
1	- $36,662,050.45
2	- $12,263,070.66
3	$8,002,723.15
4	$24,685,174.86
5	$38,268,315.33
6	$49,177,784.18
7	$57,787,446.17
8	$64,425,287.11
9	$69,378,665.67
10	$72,898,989.57
11	$75,205,877.17
12	$76,490,859.67

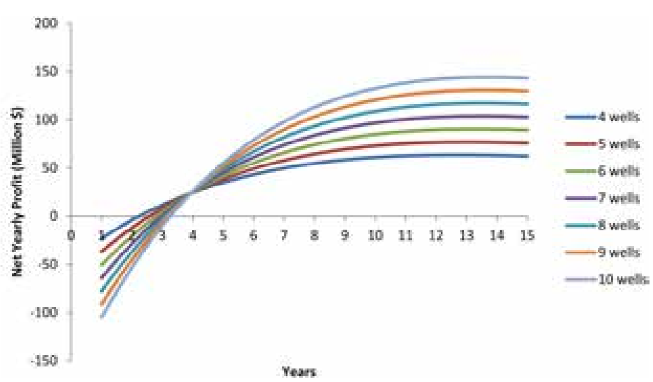


Figure 7: Net profit versus years of production.

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