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ECONOMIC MODELING OF HDR ENHANCED GEOTHERMAL SYSTEMS

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ABSTRACT

Hot Dry Rock (HDR) geothermal energy has the potential to become an important energy supply technology due to its environmental amenities and ubiquitous distribution. However, in order for HDR technology to successfully penetrate the electricity market, its cost needs to decline. The MIT Energy Laboratory, under the sponsorship of the US Department of Energy's Office of Geothermal and Wind Technologies, has created an economic model for evaluating the cost of electricity generation from HDR power systems. The model synthesizes engineering parameters (e.g., well depth, geothermal fluid flow rates, etc.) with resource characteristics (e.g., geothermal temperature gradient), reservoir performance (e.g., impedance, thermal drawdown rate), cost data, and financial parameters to calculate the cost of power production from HDR geothermal systems. The model also has the capability to optimize several engineering parameters in order to minimize costs. In this paper, we first describe the model and then discuss several case studies we have performed. We have applied the model to analyze the behavior of the experimental HDR sites at Fenton Hill, USA, at Soultz, France, and a proposed site at Hunter Valley, Australia. Based on our case studies, we identify key areas where more research is required for the improvement and, ultimately, the commercialization of HDR technologies. Finally, we develop a set of criteria in terms of resource conditions for the selection of favorable sites for future HDR development.

1. INTRODUCTION

The term "Geothermal Resources" embraces a rich variety of different energy resources in terms of fluid availability, temperature gradient, rock permeability, geological conditions, thermodynamic and hydrological characteristics. Today, most of our commercial geothermal energy comes from high-permeability, fluid-sufficient hydrothermal resources. "Enhanced Geothermal Systems" (EGS) are being developed to commercially exploit a wider range of geothermal resources. Hot dry rock (HDR) is an EGS that deals with low permeability, fluid-deficient resources. HDR resources may be classified according to their average geothermal gradient as low ($\nabla T \leq 40^oC/km$), mid ($40^oC/km < \nabla T < 60^oC/km$), or high ($\nabla T \geq 60^oC/km$) grade. HDR geothermal energy has the potential to become an important energy supply technology due to its environmental amenities and ubiquitous distribution. However, in order for HDR technology to successfully penetrate the electricity market, it needs to become more cost-competitive.

The MIT Energy Laboratory, under the sponsorship of the US Department of Energy's Office of Geothermal and Wind Technologies, has created an economic model for evaluating the cost of electricity generation from HDR power systems. We have applied the model to analyze the behavior of the experimental HDR sites at Fenton Hill, USA, at Soultz, France, and a proposed site at Hunter Valley, Australia. The cost of electricity production at these sites has been calculated for a variety of scenarios in terms of different system designs and performance.

2. MODELING APPROACH

The commercial feasibility of HDR systems is governed by multiple interdependent parameters, including:

- engineering parameters (well depth, number of wells, geothermal fluid flow rates, etc.)
- resource characteristics (geothermal temperature gradient, rock properties, etc.)
- reservoir structure and performance (number and spacing of fractures, flow impedance, thermal drawdown rate, water loss, etc.)
- cost factors (drilling, stimulation, power plant, operating & maintenance costs)
- financial parameters (discount rate, plant lifetime, capacity factor, etc.).

Our model synthesizes these elements to calculate the cost of power production from HDR geothermal systems. The model is also able to optimize the design and performance of an HDR system by determining key parameters such as the optimal drilling depth, reservoir size and geofluid flow rate. Details of the original model have been described earlier by Tester and Herzog (1991), Tester *et al.* (1994), and Herzog *et al*. (1997).

The model is accessed via a graphical user interface (GUI) designed for interactive data input and result presentation. The GUI is written in Visual Basic 6.0, while the simulator is written in Fortran 90. The software runs on Microsoft Windows with a Pentium 90MHz or higher microprocessor. At least 24 megabytes of RAM and 5 megabytes of hard disk space are needed.

3. CASE STUDIES

We have used the model to perform several case studies involving the production of electricity from HDR systems. The purpose of this analysis is to show the sensitivity of electricity price to key site characteristics and HDR system design features. For each case study, we examined several scenarios in terms of different system designs and performance. Scenario A examines the electricity production cost and performance of the HDR systems as configured. The values of the parameters used for the simulations are given in Table 1. Scenario B explores cost reductions and performance improvements as we optimize either the drilling depth, flow rate, or reservoir volume. Scenario C looks at optimizing two of these key variables at once, while Scenario D looks at optimizing all three parameters together. Finally, Scenario E takes the Scenario D results and assumes that technology improvements have rendered water losses and flow impedance levels zero.

3.1 Fenton Hill

The Fenton Hill HDR site is located in New Mexico, USA. This geographical region, due to tectonic and volcanic activity, is a high-grade resource with a temperature gradient of 65^{o}C/km. The HDR research efforts at Fenton Hill started in 1974 with the development of the "Phase I" or "Research" HDR System which did not produce enough heat for commercial exploitation. In 1979, a much larger, deeper and hotter reservoir was constructed called "Phase II" or "Engineered" HDR System (Duchane, 1991). The site was decommissioned in 1996. The values of the parameters used in our model are based on the circulation tests performed at Fenton Hill's Phase II reservoir (Duchane, 1998, 1992 and 1991; Armstead and Tester, 1987). Fenton Hill is an example of a reservoir that has the temperature gradient required for cost-effective heat mining, but does not have the flow rates required to extract the heat in a commercially viable way. The major problem of the HDR site is the high impedance to fluid circulation through the hydraulically activated fracture system. Because of its low matrix permeability, the Fenton Hill site is classified as a "closed system". A benefit is that the rate of water loss is quite small compared to the water losses of other HDR test sites. For example, the Japanese HDR site at Ogachi has reported water loss levels of about 75% of the injected flow (Duchane, 1998).

The results for this case study are shown in Table 2. Figure 1 shows how the costs can be lowered as we optimize the values of depth, flow rate, and reservoir volume. Flow rate is a key variable to render electricity production from the Fenton Hill HDR system cost effective. The reservoir volume is sufficient for the initial flow rate used, but as the flow rate increases, the reservoir size needs to increase to prevent excessive drawdown. A sufficient reservoir size is necessary to provide large amounts of available heat and, consequently, high power generation levels. An alternative approach to large initial reservoir size is to redrill the wells on scheduled intervals during the project's lifetime.

Comparing the Fenton Hill HDR system as configured to the technically optimized system, we see that the initial reservoir needs to increase seven-fold, while the production flow rate needs to increase nine-fold. A technically optimized HDR system can produce electricity at a price of 5.6¢/kWh. However, it is not clear whether the impedance to fluid circulation at the Fenton Hill site can reach such low levels that it will allow high flow rates and render the site commercially viable in the future. Field experience has shown that the reservoir is characterized by sealed natural fractures that result in very low matrix permeability. The development of permeability enhancement technologies beyond what has been achieved so far will be required for such a system to be commercially viable.

3.2 Soultz

The Soultz HDR site is located in northern Alsace, France, in the Upper Rhine Graben. The HDR project at Soultz started in 1987 under the auspices of the European Commission. The data used in this study are based on the 1996-1997 flow circulation experiments performed at Soultz. These tests showed that it was possible to maintain fluid circulation without water losses and almost no drawdown (Baumgärtner *et al*, 1998; Duchane, 1998). The fluid circulation is governed by a relatively high natural permeability of the rock mass and therefore the impedance to fluid circulation is low. Because of its higher average permeability, the Soultz site is termed as a "semi-open system", in contrast to the "closed-system" at Fenton Hill, and to the "open-systems" at the Japanese HDR experimental sites where water losses are extremely high.

In this study, instead of using a single average temperature gradient, we have used a series of temperature gradients corresponding to different depths (Baria *et al*, 1998). On average, Soultz has a geothermal gradient of about 35^{o}C/km, so it can be characterized as a low-grade resource. Power production strongly increases with the geofluid temperature, so this favors drilling deep. However, drilling costs increase exponentially with depth. Effectively, the minimal electricity price is determined by balancing drilling costs and power output. Results are shown in Table 3 and Figure 2.

Currently, the HDR site at Soultz has a large reservoir volume but at the same time the flow rate is significantly lower than what is required for power production on a commercial scale. The small amounts of heat extracted from this large reservoir result in practically negligible temperature drawdown. Increasing the flow rate can increase the reservoir productivity and as the flow rate reaches commercial levels the reservoir volume needs to increase as well. However, the impact of optimized flow rate and reservoir volume is not as important as that of optimized depth in reducing the electricity price. Drilling depth is the prominent parameter that can improve the economics of the Soultz HDR system because of the non-linear response of the overall economics to the increased temperature with depth. However, because the resource grade is low to mid-grade, even a totally optimized system would yield electricity at the relatively high price of over 11¢/kWh. Advanced drilling technology is required to lower costs further.

3.3 Hunter Valley

The Australian Hot Dry Rock Program aims to develop a commercial HDR system at Hunter Valley, New South Wales in Australia. Since there are no experimental data, the values of the model parameters are based on the HDR system as proposed to be constructed (Chopra and Wyborn, 1998; Hot Rock Energy Pty Ltd., 1997). We used a geogradient of 55^{o}C/km, which was estimated from the fact that the Muswellbrook area, where Hunter Valley is located, has an temperature of 275^{o}C at 5km depth (Hot Rock Energy Pty Ltd., 1997).

The HDR site at Hunter Valley is an intermediate situation between Soultz and Fenton Hill in terms of site characteristics. Its geothermal gradient is smaller than the one at Fenton Hill but greater than Soultz's, while the flow-impedance is smaller than the one at Fenton Hill and about the same as the one at Soultz. One characteristic of this HDR system that helps the economics is the use of two production wells per injection well compared to the one injection-one production well configuration of the experimental sites. Electric power at Hunter Valley HDR site could be generated at a cost of 5.7¢/kWh, which is similar to the estimated cost of electricity production at Fenton Hill. Since the measured flow impedance is similar to Soultz, it may be possible to reach this target.

4. CONCLUSIONS

In this work, we used a multiparameter optimization model to evaluate the economics of HDR systems. Our analysis showed that further technological improvements are necessary for HDR geothermal power systems to become cost effective. The prominent parameter that can improve the economics of low-grade resources is drilling cost (or depth), whereas in high-grade resources it is the flow rate and the reservoir size. Our analysis shows that for a geothermal site to be suitable for HDR development, it requires a mid to high-grade resource, low flow-impedance levels, small water loss rates, and sufficient reservoir volumes. For high-grade resources, HDR power systems can approach commercially acceptable levels in the electricity supply market (similar to wind technology today) if research efforts lead to flow impedance reductions and acceptable water losses. In many reservoirs settings, water losses and impedance can be controlled through proper well placement and appropriate pressure management. For mid to low-grade resources, advanced (i.e., less expensive) drilling technology is also required. For that reason, R&D programs should focus on the development of improved reservoir definition, formation and stimulation techniques. Field experimentation should be continued to attain the reservoir productivity levels needed for commercialization. Our analysis showed that the use of multiple production wells per injection well can improve the productivity and the economics of an HDR system. The concept of triplet and star well configurations should be tested on site. Finally, the development of advanced drilling technologies to lower costs is critical to be able to economically access the deep reservoirs required for commercial operations in low to mid-grade resources.

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Table 1. Values of the parameters for the HDR sites at Fenton Hill (USA), Soultz (France), Hunter Valley (Australia)

Parameter	**Fenton Hill**	**Soultz**	**Hunter Valley**
Average geothermal gradient	65°C/km	105°C/km (z<.9km) 15°C/km (.9<z<2.35km) 30°C/km (z>2.35km)	55°C/km
Drilling depth	4 km	3.9 km	4.5 km
HDR system configuration	Doublet	Doublet	Triplet
Number of fractures per well-pair	5	17	5
Well separation	380 m	450 m	500 m
Fracture separation	40 m	47 m	250 m
Water loss rate	7%	0%	2%
Circulation pump efficiency	80%	80%	80%
Temperature drop in production well	15°C	15°C	15°C
Injection Well Casing ID	7" (17.8 cm)	7" (17.8 cm)	10" (25.4 cm)
Production Well Casing ID	7" (17.8 cm)	7" (17.8 cm)	7" (17.8 cm)
Injection Temperature	55°C	55°C	55°C
Fluid flow rate per production well	10 kg/s	25 kg/s	75 kg/s
Impedance per fracture	3.5 GPa-s/m^3	1.5GPa-s/m^3	1.5GPa-s/m^3
Capacity factor	90%	90%	90%
Fixed charge rate	15%	15%	15%
Plant Life	20 years	20 years	20 years

Table 2. Results of the different scenarios for HDR system at Fenton Hill

Scenario	**A**	**B**			**C**			**D**	**E**
Characteristic	HDR system as configured	Optimized depth	Optimized flowrate	Optimized reservoir volume	Optimized depth & flowrate	Optimized depth & reservoir volume	Optimized flowrate & reservoir volume	Possible re-engineered HDR system	Technically optimized HDR system
Well Depth (km)	4	4.8	4	4	4.8	4.8	4	4.8	4.8
Production Flowrate (kg/s)	10	10	18.7	10	21.5	10	64.5	81.5	90.4
Reservoir Volume (million m^3)	18	18	18	16.6	18	14.4	97.4	114.7	118.8
Production Temperature[1] (°C)	255/253	307/306	255/211	255/253	307/239	308/304	232/216	279/257	278/248
Electric Power[1] (MWe)	1.53/1.51	2.38/2.36	2.70/1.47	1.54/1.50	5.02/2.57	2.40/2.32	6.91/5.41	14.4/11.4	17.0/12.6
Electricity breakeven price (¢/kWh)[2]	19.9	17.8	14.8	19.9	11.7	17.6	8.7	6.4	5.6

[1] Decreases over time due to drawdown of reservoir. First number is for year 1, second number is for year 20.

[2] In 1997 $ US

Table 3. Results of the different scenarios for the HDR system at Soultz

Scenario	A	B			C			D	E
Characteristic	HDR system as configured	Optimized depth	Optimized flowrate	Optimized reservoir volume	Optimized depth & flowrate	Optimized depth & reservoir volume	Optimized flowrate & reservoir volume	Possible re-engineered HDR system	Technically optimized HDR system
Well Depth (km)	3.9	6.69	3.9	3.9	7.62	6.46	3.9	7.85	7.76
Production Flowrate (kg/s)	25	25	55	25	84	25	51.5	111	114.5
Reservoir Volume (million m^3)	119.6	119.6	119.6	55.8	119.6	46.6	105	199	197
Production Temperature[1] (°C)	152/152	235/235	152/148	158/156	263/233	235/229	153/148	262/250	260/244
Electric Power[1] (MWe)	0.68/.18	3/3	1.15/1.02	0.73/0.69	13/9	3.1/2.9	1.13/0.96	15.9/13.6	16.5/13.7
Electricity breakeven price (¢/kWh)[2]	47.9	29.0	32.2	40.9	13.1	26.0	32.1	12.1	11.4

[1] Decreases over time due to drawdown of reservoir. First number is for year 1, second number is for year 20.

[2] In 1997 $ US

Table 4. Results of the different scenarios for the HDR system at Hunter Valley

Scenario	A	B			C			D	E
Characteristic	HDR system as projected	Optimized depth	Optimized flowrate	Optimized reservoir volume	Optimized depth & flowrate	Optimized depth & reservoir volume	Optimized flowrate & reservoir volume	Possible re-engineered HDR system	Technically optimized HDR system
Well Depth (km)	4.5	5.67	4.5	4.5	5.67	5.67	4.5	5.67	5.67
Production Flowrate (kg/s)	75	75	59	75	72	75	54	78	95
Reservoir Volume (million m^3)	500	500	500	572	500	554.8	429.7	586	610
Production Temperature[1] (°C)	220/200	284/264	220/213	216/203	284/267	281/267	224/215	279/265	278/252
Electric Power[1] (MWe)	11/7	26.56/21.35	9.75/8.53	10.7/8	25.68/21.47	26/22.37	9.58/8.21	26.65/22.82	36.23/28.51
Electricity breakeven price (¢/kWh)[2]	11.1	6.8	10.3	10.8	6.7	6.7	10.2	6.7	5.7

[1] Decreases over time due to drawdown of reservoir. First number is for year 1, second number is for year 20.

[2] In 1997 $ US

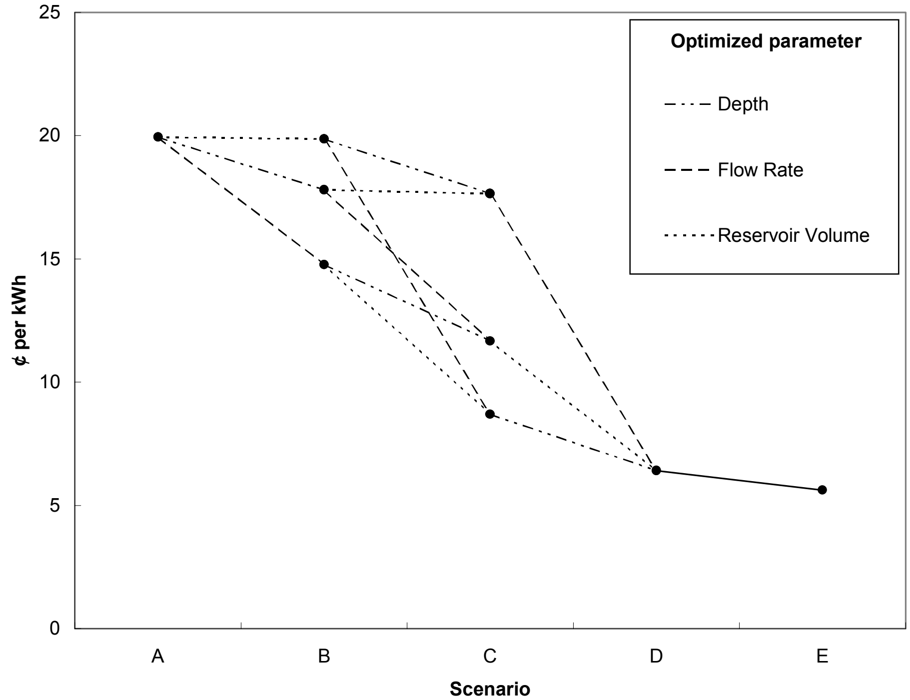

Figure 1. Electricity Prices (1997 $) for the HDR site at Fenton Hill. Data plotted is from the last row of Table 2 in 1997 $. Note how the price decreases as we increase the number of design parameters optimized. The type of line indicates which parameters were optimized.

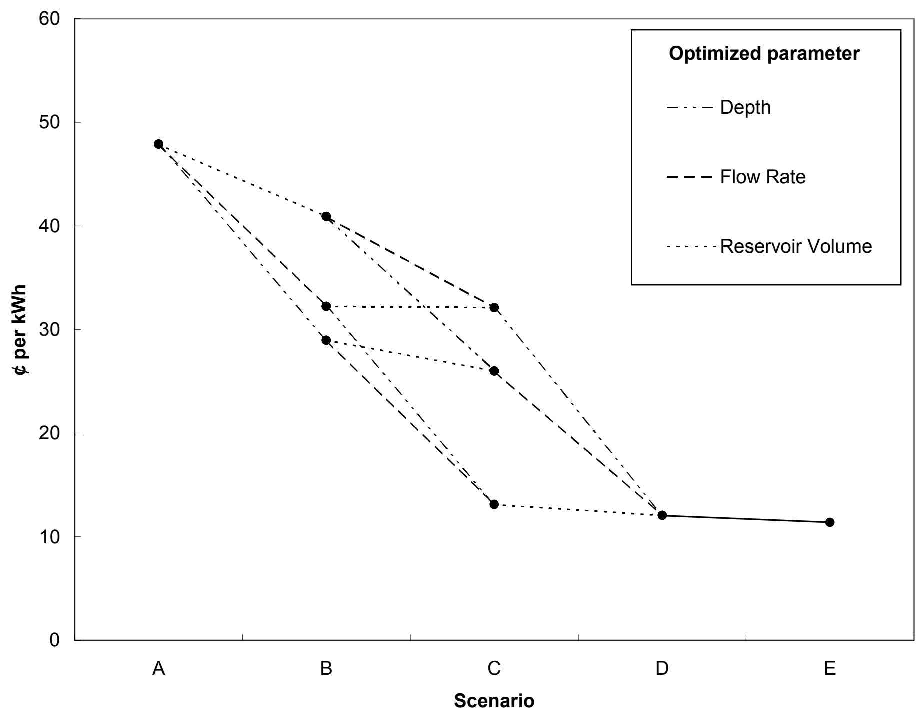

Figure 2. Electricity Prices (1997 $) for the HDR site at Soultz. Data plotted is from the last row of Table 3 in 1997 $. Note how the price decreases as we increase the number of design parameters optimized. The type of line indicates which parameters were optimized.