PROCEEDINGS, Thirty-Fifth Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, February 1-3, 2010
SGP-TR-188

A SYSTEM DYNAMICS APPROACH FOR EGS SCENARIO ANALYSIS

Thomas S. Lowry[1], Vincent C. Tidwell[1], Peter H. Kobos[1], Mark Antkowiak[2], Charles Hickox[1]

[1]Sandia National Laboratories
P.O. Box 5800 MS 1137
Albuquerque, NM 87185, USA
e-mail: tslowry@sandia.gov

[2]National Renewable Energy Laboratory
1617 Cole Blvd.
Golden, CO 80401, USA

ABSTRACT

In order for enhanced (or engineered) geothermal systems (EGS) to become commercially viable, many technical and economic hurdles must be overcome. Prioritizing which hurdles to address first is extremely important since the distance gained towards understanding EGS varies based on which hurdle is cleared. Complicating this situation is the fact that most of these technical and economic hurdles, as well as the gains that their understanding contributes towards the goal of commercializing EGS, are dependent variables, meaning that they exist in dynamic relationship with other processes. This complexity creates feedback and non-linear behavior that makes assessment and evaluation extremely difficult. To address this issue, a system dynamics (SD) approach has been employed to create an EGS scenario analysis model. SD models are unique in their ability to focus on the temporal dynamics while accounting for the various feedback loops and delays that are inherent in complex integrated systems such as EGS. A systems approach also has the general advantage of reduced computational burden and thus the opportunity to develop interactive models that operate in real time on a PC or across the web, allowing broad stakeholder engagement.

The model provides a basis for defining the technical and economic solution space for EGS across a variety of well, reservoir, and power plant configurations. Utilizing the Geothermal System Scoping Model developed by NREL as one of its key sub-models, the SD model has the ability to communicate with the Geothermal Electricity Technology Evaluation Model (GETEM) to provide baseline economic evaluations of the different scenarios. In this way, the SD model is able to identify the integrated technical and economic bottle necks and uncertainties associated with developing EGS.

INTRODUCTION

From the perspective of available resource, the prospect of the amount of energy generated from enhanced geothermal systems (EGS), which allows for the exploitation of the Earth's heat, is positive, given that estimates of the EGS resource to a depth of 10 km in the U.S. alone are over 100,000 times the nation's annual consumption (MIT, 2006). However, when tasked with harnessing an EGS resource in a commercially competitive manner, the prospects are not so optimistic. What distinguishes EGS from most other energy sources is the difficulty and expense associated with characterizing, accessing, and then harnessing the energy.

Taken to its extreme, we know that if we drill deep enough, a thermal source capable of generating huge amounts of energy exists. However, the costs associated with accessing that resource are clearly uneconomical. In addition, depending on the actual depth and temperature, the technology might not exist for reliable operations. Thus, tradeoffs must be made between the costs in terms of time and money needed to access and harness a resource against the production of both energy and dollars. If enough energy can be produced, at a levelized cost of electricity (LCOE) that is reasonably competitive, then that resource is most likely exploitable. The difficulty comes in evaluating those tradeoffs, especially in the face of competing technologies that are currently market-competitive.

To illustrate this, consider a 100 ^{o}C geothermal resource at 1 km depth with a 2.5 ^{o}C per 100 m geothermal gradient, which is a realistic but relatively low gradient (MIT, 2006). By drilling deeper, one could gain access to a 150 ^{o}C source at 3000 m, or a 250 ^{o}C source at 7000 m. Since the source temperature greatly impacts the power generation capabilities, a tradeoff exists between drilling deeper to gain access to the higher temperature resource and the drilling costs. If one drills too deep, the drilling

costs will outweigh the benefit of obtaining the higher temperature source. If one drills too shallow, then the ability to generate enough energy to warrant development may be compromised. Given this simple example, it is easy to see an optimal depth exists where the drilling costs are minimal enough, and the resource temperature great enough, to warrant development.

Unfortunately, real world conditions are not that simple. The two fixed variables from above, drilling costs and temperature gradient, are dynamic, composite variables, meaning that they are time varying functions of other, more fundamental variables, many of which are also dynamic, composite variables themselves. Thus, when looking at drilling costs, one might need to consider the rock type(s), the operating temperature, the cost of steel, the size of the borehole, and so on. And while the temperature gradient informs us of the temperature of the resource, it says nothing about our ability to stimulate the reservoir and extract the heat, which determines the size of the power plant that could be installed at that location. Additional complexity arises when one considers the connections between the fundamental variables, such as how the borehole diameter, which impacts drilling costs, also impacts the mass flow rate, which in turn impacts the heat extraction and ultimately power production.

To address this issue, we have employed a system dynamics (SD) approach to create an EGS scenario analysis model that allows a user to perform tradeoff and scenario analyses in real time. This allows them to identify the optimal solution space for a given set of resource characteristics, and power plant and well configurations. This paper documents what has been our initial effort in this project by first describing the objectives of our efforts from both a scientific and programmatic point of view. Following that is a discussion of our approach, which includes a description of system dynamics and how it is applied to EGS. We end the paper by presenting some deterministic results that come from examining a single scenario, as well as some risk assessment results that come from a probabilistic analysis.

PROJECT OBJECTIVES

The primary objective of this work is to develop a systems based tool for performing tradeoff and scenario analysis of EGS. Underlying this objective are several sub-objectives which are to identify, 1) the physical parameter space for an EGS project, 2) gaps in our understanding of EGS and the salient available technologies, and 3) the interactions and feedbacks amongst the physical and socio-economic parameters that control the affordability of EGS.

The work described here is the first task of a larger project, which was to test the utility and effectiveness of systems analysis for geothermal energy by examining a relatively narrow but critical aspect of EGS.

EGS SCENARIO ANALYSIS AND SYSTEM DYNAMICS

The work presented here concentrates on EGS and more specifically, the utility and effectiveness of applying a system dynamics approach to evaluating this resource. With reference to the models simulation capabilities, EGS means the entire EGS cycle, excluding the power plant. Thus, the model simulates the flow and transport of heat and the geofluid at the point it leaves the power plant as cooled effluent, to when it enters the power plant as a heated production fluid. The conceptual model of the EGS system is illustrated in Figure 1.

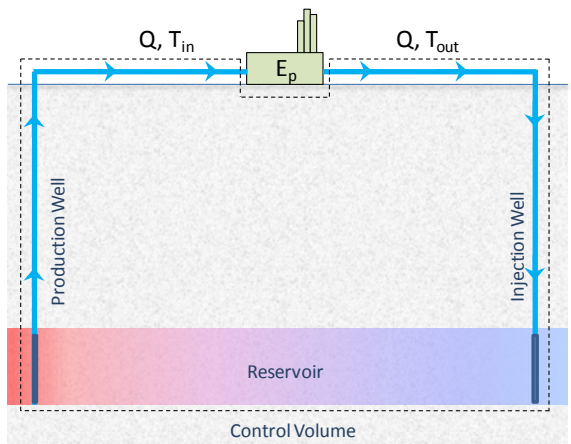

Figure 1: Conceptual model of the EGS cycle. The model simulates heat and brine flow and transport for the area inside the dotted line.

System dynamics (SD) is a modeling approach that allows for the simulation and quantification of the temporal relationships between disparate yet connected systems and sub-systems, the collection of which makes up the 'grand' system of interest. General consensus points to SD being founded as a separate discipline by J. Forrester (Forrester, 1971), who originally developed the approach for application to the business world to track the stocks (i.e. inventories) and flows of different commodities. System dynamics provides unique insight into the macro-behavior of the grand system by simulating the temporal behavior of the sub-systems. It is the temporal behavior of the sub-systems, and the feedbacks and delays that are inherent in their relationship to one another, that creates the complexity and non-linear behavior that is so difficult

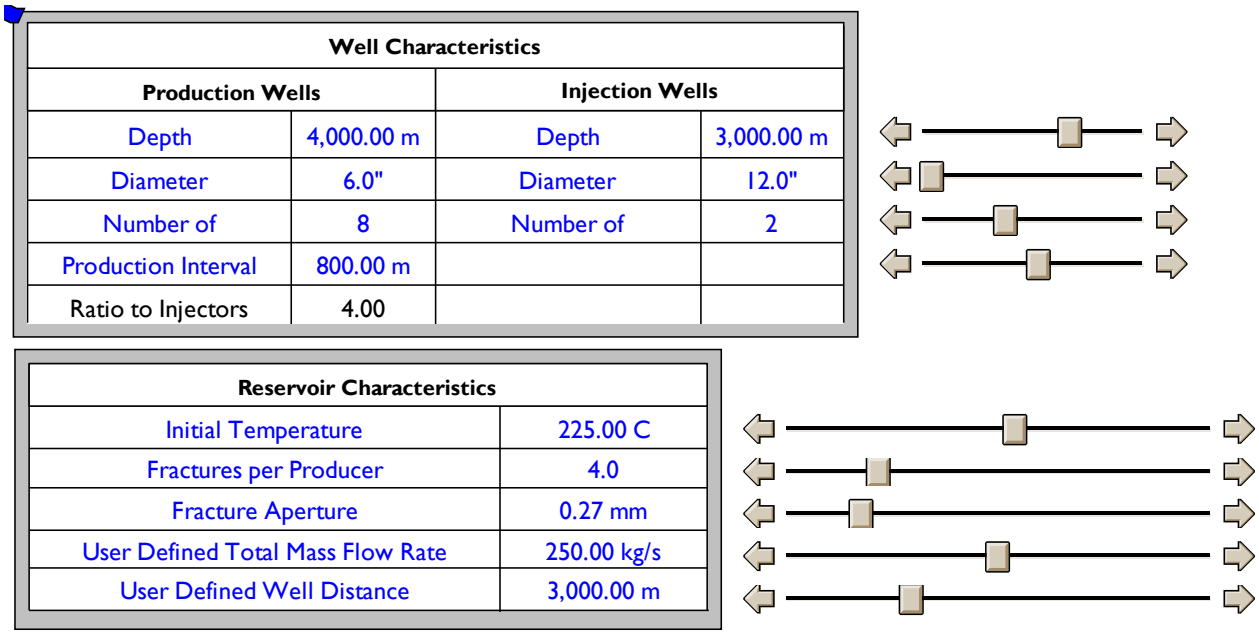

Figure 2: Screen shot of a portion of the user interface for changing parameters associated with production and injection wells as well as the reservoir characteristics.

to contend with. Without this integrated, systems oriented approach, the ability to assess the benefits and tradeoffs of the endless combinations of current and future technological, spatial, and socio-economic aspects of bringing a geothermal resource to market is difficult at best.

SIMULATION DYNAMICS

In its current state, the model simulates the entire EGS cycle with the exception of the power plant, which is treated as a 'black-box' entity. Through a graphical user interface (Figure 2), a user is able to enter the generating capacity and utilization efficiency of the power plant, the depth and temperature of the resource, as well as other physical parameters such as pipe and borehole diameters, reservoir characteristics, operating temperatures, and so on. The user has the option of allowing the tool to estimate the required size of the reservoir and the mass flow rate based on the generating capacity and efficiency of the plant (Antkowiak et al., 2010). Alternatively, the user can input values for each of those parameters. Independent of how the initial mass flow rate is calculated, the user also has the option of allowing the model to increase the mass flow rate over time to maintain a consistent capacity level, or to fix the mass flow rate, at which point the power generation rate would decrease as the temperature of the production fluid declines over time. Table 1 lists the current user inputs to the model.

Once parameterized, the model will simulate the flow and transport of brine and heat through the entire EGS cycle beginning with the effluent outflow from the power plant and ending with the production fluid inflow to the power plant. The model currently assumes that pressures are high enough to prevent the geofluid from flashing at any point along the cycle (i.e. the brine is in liquid form throughout the cycle). That assumption will change in future versions.

Table 1: List of user definable inputs to the EGS systems analysis model. "P&I" refers to production and injection wells and "PP" refers to power plant.

Resource depth [m]	Ground elevation [m]
Resource temperature [°C]	P&I well diameters [in]
Average fracture aperture [mm]	Number of P&I wells
Production interval [m]	Production interval [m]
Distance b/t wells [m]	P&I depths [m]
PP capacity [MWe]	PP effluent pipe diameter [in]
PP life expectancy [yrs]	PP influent pipe diameter [in]
PP utilization efficiency [%]	PP effluent pipe length [m]
PP minimum operating temperature [°C]	PP influent pipe length [m]
Elevation changes between PP and P&I wells	Reinjection temperature [°C]

The model simulates the pressure distribution and brine temperature along the EGS loop. The current approach calculates pressures using the standard Darcy-Weisbach equation (e.g. Chin, 2000) with the Jains approximation for the friction factor (Jain, 1976). Current options for simulating the heat exchange in the reservoir, are the Carslaw and Jaeger solution for simulating single, non-interacting fractures, or the Gringarten solution for simulating multiple fractures (Carslaw and Jaeger, 1959;

Gringarten et al., 1975). Head loss in the reservoir is calculated using the Snow estimate for permeability of a fractured medium (Snow, 1968). We anticipate adding more complex and realistic algorithms for each of these processes in future versions of the model.

The model simulation begins with an initialization period where all time varying parameters are kept constant and the pressure distribution is allowed to reach steady state. This is necessary since the pressure distribution cannot be calculated directly. For the initial guess, the pressure distribution is assumed to follow the elevation head profile of the EGS system. Once initialized, the model forecasts for a period equal to the user defined life-span of the power plant (up to 50 years). The user can end the simulation there, or continue beyond the power plant's life-span for the balance of time to reach 50 years. If the production temperature falls below a user defined minimum operating temperature for the plant, then the simulation will pause and issue a warning.

The output variables are the production temperature, the pressure distribution, the energy grade line along the length of the EGS cycle, power production, plant efficiency, and thermal drawdown. Each of the output variables are displayed as a time series with the exception of the thermal drawdown rate, which is a single value calculated at the end of the simulation. The thermal drawdown rate is calculated as the absolute value of the exponential rate coefficient that reproduces the beginning and ending temperatures of the reservoir.

The model has two modes of operation, deterministic and stochastic. The deterministic mode allows a user to create individual scenarios and run them one at a time to see how the system performs for each different scenario. A scenario is defined as a set of input parameters that describes a unique configuration or possible development plan. In stochastic mode, the user defines a probability density function (PDF) for one or more input variables, and designates one or more output variables to be viewed. Using a Latin hypercube sampling approach, the model systematically steps through the range of input values for any input variable that has been assigned a PDF. When in stochastic mode, the selected output variables are displayed as a statistical distribution that describes the variability of the output (e.g., mean and standard deviation) that results from the range of inputs. The stochastic mode can also be thought of a type of uncertainty analysis since uncertainty in the input variables is directly translated to uncertainty in the output variables.

MODEL EXAMPLES

To illustrate the use of the model, two examples are shown. The first example shows results from three scenarios generated using the deterministic mode of simulation. Each of the scenarios is based on a 20 MW_e power plant, operating at a 13% utilization efficiency. The plant is tapping a 225 ^oC resource at a depth of 4 km. Production and injection wells are fixed to be 3000 m apart. The difference between the scenarios is the number of injection and production wells; scenario 1 uses 2 injection wells and 4 production wells, scenario 2 uses 4 injection wells and 4 production wells, and scenario 3 uses 2 injection wells and 8 production wells. The diameters of the wells were adjusted for each scenario to maintain the same total cross-sectional area for the injection and production wells alike.

Figure 3 shows the energy grade line along the length of the EGS cycle at the end of the 30 year life span of the power plant. The energy grade line is the sum of the pressure head, the velocity head, and the elevation head. The elevation head was calculated assuming a 0 m elevation for the power plant. For the pipes and the wells, the difference between the energy grade line at its start and end points is the frictional head loss. For the reservoir however, thermal energy is added to the water, so the difference between the start and the reservoir equals the added thermal energy minus the frictional head loss. Examining the figure, scenario 3 shows a strong gain in energy through the reservoir, while the other scenarios show a slight decline.

The gain through the reservoir can be explained by examining Figure 4, which shows the change in the production temperature over time. Since the model assumes a fixed number of fractures per producer, adding more producers has the equivalent effect of accessing additional area in the reservoir (i.e. the reservoir volume is scaled with the number of producers). The additional area accessed by the added producers in scenario 3 results in a much smaller temperature decline, which in turn results in a lower head loss through the reservoir, mainly due to the higher hydraulic conductivity that is associated with the higher temperature fluid. Since the number of producers for scenarios 1 and 2 are the same, the temperature change over time is almost identical. Figure 5 shows the result of the temperature decline in the form of a loss in power production over time.

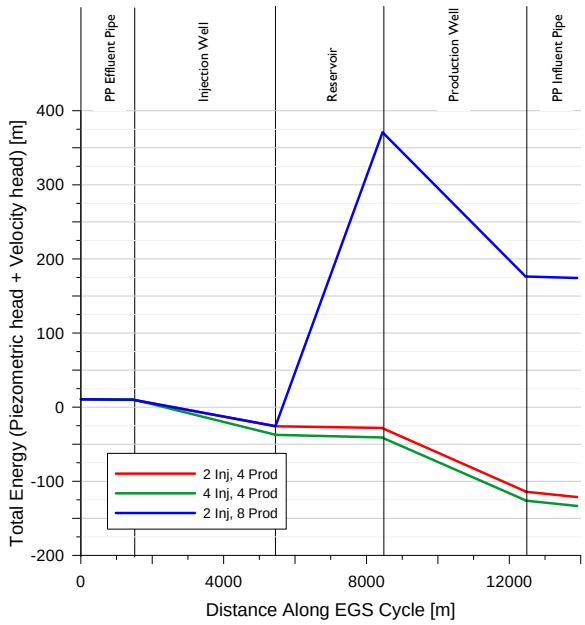

Figure 3: The energy grade line along the length of the EGS cycle at the end of the simulation. The drop in energy across the reservoir for scenarios 1 and 2 indicate that the thermal energy added is less than the frictional head loss across the reservoir. This condition only exists for the last few years of the simulation, after the reservoir temperatures had declined.

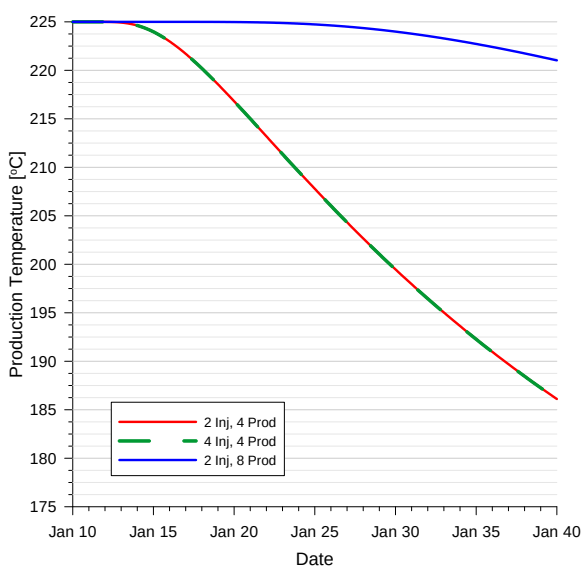

Figure 4: The change in production temperature over time for each of the scenarios. Due to a higher number of producers, scenario 3 is able to access a higher volume of reservoir and thus experiences a slower decline than the other scenarios.

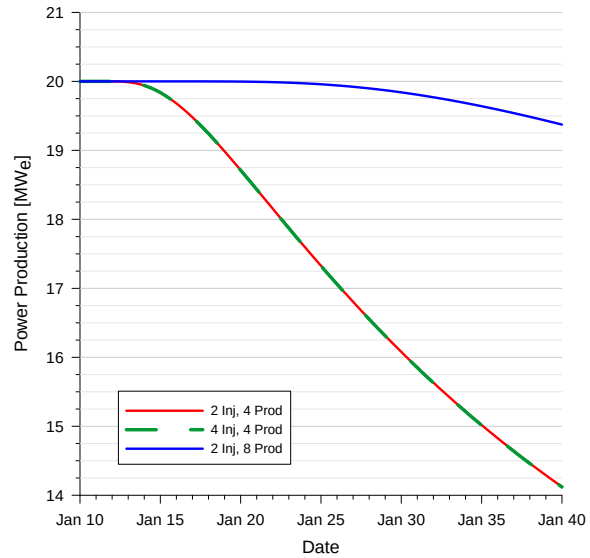

Figure 5: The change in power production for the different scenarios is mainly due to the decline in the production fluid temperature over time.

The second example is a stochastic simulation using the parameters of scenario 3. A normal probability distribution function is defined with a mean of 3000 m and a standard deviation of 300 m for the distance between the production and injection wells. The stochastic simulation is set to perform 40 simulations using Latin Hyper Cube sampling and to output the average, 95, 75, 25, and 5 percentile values for power production, production temperature, and total head loss (Figures 6, 7, and 8).

The figures show that the range of production temperatures as a function of the distance between the wells is somewhat skewed to the lower end, indicating that the relative changes between the distance between the wells and the production temperature is non-linear. The total head loss plot also shows a non-linear relationship but the effect is not as great.

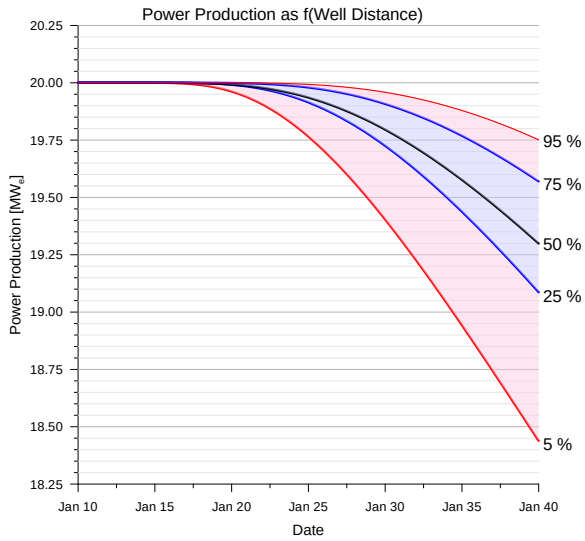

Figure 6: Power production over time as a function of a normally distributed distance-between-wells input parameter.

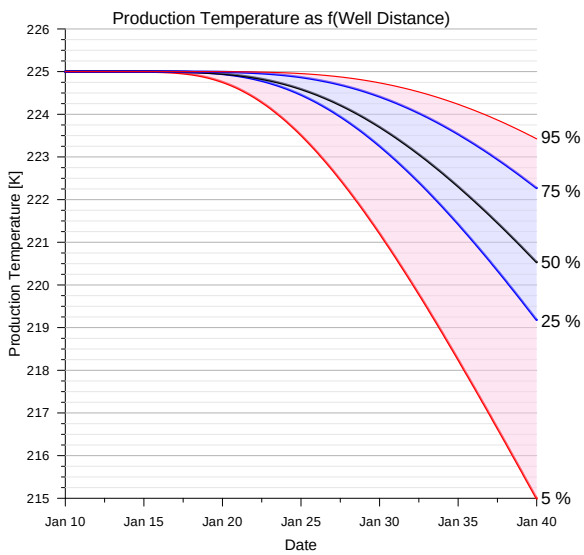

Figure 7: Production temperature over time as a function of a normally distributed distance-between-wells input parameter.

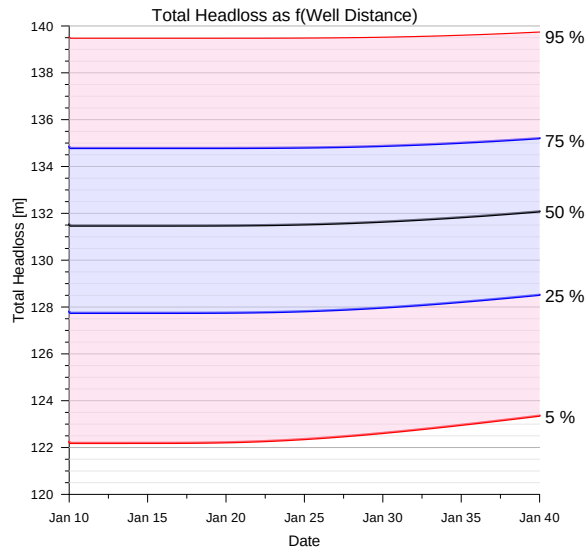

Figure 8: Total head loss for the EGS cycle over time as a function of a normally distributed distance-between-wells input parameter.

CONCLUSION AND FUTURE WORK

The work presented here was to demonstrate the utility and effectiveness of systems analysis for geothermal resource assessment by examining an EGS project. Through a user friendly interface, users are able to adjust multiple parameters to create custom scenarios that can then be dynamically simulated over time to evaluate the physical performance of the EGS. Uncertainty propagation can also be evaluated by defining PDF's for one or more variables and seeing the impact of that uncertainty on the output.

Ongoing work for this project is focused on the inclusion of the entire suite of EGS engineering and development considerations. Ultimately, we envision a fully integrated decision platform tool that will be served to the public and stakeholders across the web or for distribution and use on personal computers. The tool will allow for full tradeoff and scenario analysis across the entire range of geothermal technologies that would include low temperature, hydrothermal, geothermal heat pumps, and co-produced fluids.

The ongoing work also includes a spatial aspect that will map the output from the scenario analysis to the county, state, and/or national level. The mapping will consist of a series of dynamic 'GIS type' layers that will detail the spatial limitations associated with a particular resource by delineating key metrics important to energy production; for example, temperature of the host rock, depth of resource, exploration costs, water availability, distance to electrical transmission lines, land ownership,

environmentally sensitive habitat, etc. The tradeoff and scenario analysis modules that address the heat extraction process and the conversion of the resource to usable energy, etc. will be integrated into the spatial analysis to provide spatially varying estimations (i.e. contour maps) of plant performance, efficiency, costs, and the LCOE across the entire US.

The LCOE estimations would then be rolled-up to give detailed cost curves (LCOE per MW of power produced) at both a national and regional level. Two sets of curves will be developed; the first using the current available technologies (e.g., cost to drill, efficiency factors, permitting expenses, etc.) and resource data, and the second using user defined potential changes due to new technologies and/or improved resource data. In this way, a user will be able to determine the technologies and/or data that if improved, would have the highest potential for impact while also examining what level of development would be necessary to bring a geothermal resource to market.

REFERENCES

Antkowiak, M., Snyder, N. K. and Lowry, T. S. (2010). "A High Level Geothermal System Scoping Model: A First Step Toward Enhanced Geothermal Systems Engineering". *35th Stanford Geothermal Workshop*, February 1-3, Stanford, CA.

Carslaw, H. S. and Jaeger, J. C. (1959). "Conduction of Heat in Solids". Oxford, Clarendon Press.

Chin, D. A. (2000). "Water-Resources Engineering". Upper Saddle River, NJ, Prentice-Hall Inc.

Forrester, J. W. (1971). "Principles of Systems". Cambridge, MA, Wright-Allen.

Gringarten, A. C., Witherspoon, P. A. and Ohnishi, Y. (1975). "Theory of Heat Extraction from Fractured Hot Dry Rock." *Journal of Geophysical Research* **80**(8).

Jain, A. K. (1976). "Accurate explicit equation for friction factor." *Journal of the Hydraulics Division* **102**(HY5): 674-77.

MIT (2006). "The Future of Geothermal Energy: Impact of Enhanced Geothermal Systems (EGS) on the United States in the 21st Century. An assessment by an MIT-led interdisciplinary panel." Massachusetts Institute of Technology http://geothermal.inel.gov

Snow, D. T. (1968). "Rock fracture spacings, openings, and porosities." *Journal of the Soil Mechanics and Foundations Division, Proceedings of American Society of Civil Engineers* **94**: 73-91.