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INTEGRATED RISK ASSESSMENT FOR GEOTHERMAL ENERGY DEVELOPMENT AND EVALUATION

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ABSTRACT

This study uses a risk-assessment approach to examine how uncertainty and risk change as a function of the thermal drawdown calculation for an enhanced geothermal system (EGS). Using Monte-Carlo simulations, we calculate the uncertainty and integrated risk of the levelized cost of electricity (LCOE) that results from uncertainty in a variety of sub-surface parameter values. Three ensembles of simulations are created, each with the same uncertainties in the sub-surface parameter values but with different methods of calculating the thermal drawdown. Integrated risk assessment is an approach that simultaneously accounts for all uncertainties and other outside factors that may cause the actual future to deviate from its predicted future. Integrated risk is calculated as the sum of the consequence, C, multiplied by the range of the probability, ΔP, over all estimations of a given exceedance probability, n, over time, t. Here, consequence is defined simply as the LCOE, with the probabilities of achieving a particular LCOE a function of the uncertainty. The analysis assumes a realistic but fictitious EGS site with nine varied parameters that control the sub-surface conditions. A risk-based LCOE value is calculated for each ensemble along with correlation analysis to identify the parameters and conditions that contribute most to the risk.

INTRODUCTION

Without any real-world experience to draw from, estimates of the competitiveness of EGS, in the form of the levelized cost of electricity (LCOE), have relied on a set of assumptions about the sub-surface and thermal performance. Large uncertainties exist regarding our ability to stimulate a site as well as the resulting thermal performance over time. Uncertainty analyses of economic, operational, and geological conditions have been performed in the past to try and understand their influence on the predicted LCOE values. However, one area of uncertainty that has been overlooked has been numerical uncertainty; the uncertainty introduced through the numerical approach used to estimate the thermal performance of a reservoir over time.

Here, we begin to quantify this uncertainty by comparing quantitative risk assessments using three thermal drawdown models; an assumed annual percentage decline, the Carslaw and Jaeger (Carslaw and Jaeger 1959) single fracture analytical solution, and the Gringarten (Gringarten, et al. 1975) multiple fracture analytical solution. Two hundred and fifty simulations with each solution method were performed with each simulation using a randomly selected set of parameters that describe the sub-surface conditions at the site.

The simulations were completed using GT-Mod (Lowry, et al. 2010), an integrated systems modeling tool developed at Sandia National Laboratories that dynamically links the various systems and sub-systems of a geothermal project to simulate the collective performance of each system over time. Built using a system dynamics framework, the various systems contained in GT-Mod are simulated as individual modules that communicate with each other through dynamic linkages that define the interdependencies between them. Each module addresses a particular process such as thermal drawdown, pressure losses in the wells, power generation, cooling facilities, etc. and contains one or more sub-models with similar characteristics. GT-Mod simulates the time varying pressure regime, thermal drawdown, plant performance, and economics as a single, system of systems. Economic analysis is accomplished through a real-time, two-way connection to a modified version of the Geothermal Energy Technology Evaluation Model (GETEM) (Entingh, et al. 2006) that calculates the levelized cost of electricity based on time-series performance output from GT-Mod.

GT-Mod is unique in that it allows a user to define a probability distribution function (PDF) for any number of input variables. The inputs can be defined using uniform, normal, log-normal, truncated normal, exponential, or triangular distributions. GT-Mod uses a Monte Carlo approach to propagate the input uncertainties to the output by varying each of the input PDF's across its range of values via a Latin Hypercube Sampling (LHS) technique.

Output from the simulations are collected and processed to remove simulations that did not converge as well as those where the thermal drawdown exceeded the minimum operating temperature of the power plant. For each ensemble, a cumulative probability function of the LCOE is created and the quantitative risk is calculated. It is from these values that the differences in the solution method is explored and further analyzed.

INTEGRATED RISK

Generally, uncertainty manifests in both the inputs and the outputs of an analysis. For the inputs, uncertainty reflects the confidence that the value of an input is the 'true' value for the analysis in question. Uncertainty in the outputs result from the propagation of input uncertainties, the assumptions used to create the simulation algorithms, and numerical inaccuracies in the solution method. The risk assessment approach used here, quantitative risk assessment, is similar to that used by the insurance industry to assess their exposure to loss and can be thought of as a method that quantifies the influence of uncertainties in the inputs on the range of outputs.

Quantitative risk assessment relies knowing the consequence(s) of an event (or set of events) as well as the probability of that event occurring. To quantify risk, we utilize the approach introduced by Helton (1994) who defines risk as the sum of the consequence, C, multiplied by the range of the probability, ΔP, over all estimations of a given exceedance probability, n, over time, t:

$$R = \sum_{t} \sum_{n} C(n,t) \Delta P(n) \qquad (1)$$

The risk calculated with equation (1) represents an integrated risk meaning that the risk is the sum of the risk for all events that have a less than or equal probability of occurring than some reference event. For our purposes, an 'event', or scenario, is a single combination of input parameters. Quantifying risk allows for directly comparing different scenarios and allows one to compare the tradeoffs between lower-probability higher-reward scenarios versus higher-probability lower-reward scenarios.

THE ANALYSIS

The analysis is based on a fictitious EGS site configured to produce 30 MWe at the start of the simulation. The mass flow rate is constant throughout each simulation so the electricity production drops over time as a consequence of the declining production temperature. The thermal gradient is assumed constant at 43 ^{o}C/km, which gives a temperature of 225 ^{o}C at a depth of 5000 km (assuming a 10 ^{o}C ground surface temperature). Nine parameters controlling the sub-surface conditions are defined using probability functions and are randomly sampled for each simulation as described above. The variable parameters are the resource depth, the production well mass flow rate, the stimulated volume (defined by the reservoir width and height), the number of fractures, the fracture aperture, the rock thermal conductivity, the rock specific heat, and the rock density.

As the resource depth is varied, the resource temperature is adjusted accordingly, as is the design and minimum operating temperatures of the power plant. The number of wells for each simulation is based on the 30 MWe power output, and the brine effectiveness, which is calculated using a regression against the design temperature. Variations in the mass flow rate, the number of fractures, and the fracture aperture impact the hydraulic drawdown and thermal performance of the reservoir. The hydraulic drawdown and depth of the resource influences whether or not pumping is needed and whether it is on the injection side, the production side, or both. Hydraulic drawdown is calculated using the Snow (1968) estimation. Each of the varied parameters and their associated PDF is listed in **Error! Reference source not found.**. All other sub-surface parameters are kept constant, as are parameters describing the economics, operations, and maintenance costs.

The Gringarten solution is a function of the initial resource temperature, number of fractures, fracture aperture, fracture spacing, mass flow rate, and the thermal properties of the rock. It is assumed that the mass flow rate in the single fracture used in the Carslaw and Jaeger solution is the total mass flow rate divided by the number of fractures. Thus the only difference in the Gringarten and Carslaw and Jaeger solutions is the dynamic between adjacent fractures that is captured by the Gringarten solution. The annual decline rate solution method is the same used in GETEM and assumes a constant, yearly percentage change for the length of the simulation. The simulations for the annual decline rate ensemble

Table 1 - Listing of the variable parameters, the distribution type, and the distribution parameters used in the analysis. For the truncated log-normal distribution, the distribution parameters reflect the log-transformed value of the indicated unit.

Name	Unit	Distribution Type	Distribution Parameters
Resource Depth	m	Normal	Mean: 5000 Std Dev: 400
Production Well Mass Flow Rate	Kg/s	Truncated log-normal	Mean: 3.95 Min: 3.17 Std Dev: 0.7 Max: None
Stimulated Width	m	Uniform	Min: 600 Max: 1000
Stimulated Height	m	Uniform	Min: 150 Max: 250
Number of Fractures	-	Uniform	Min: 2 Max: 10
Fracture Aperture	mm	Truncated log-normal	Mean: -1.61 Min: -2.99 Std Dev: 0.6 Max: 0
Rock Thermal Conductivity	W/m*^{o}C	Normal	Mean: 2.85 Std Dev: 0.38
Rock Specific Heat	kJ/kg*^{o}C	Uniform	Mean: 0.95 Std Dev: 0.05
Rock Density	Kg/m^3	Uniform	Mean: 2700 Std Dev: 18

were set to return the average end temperature of the other two solution methods.

RESULTS

Results for this analysis are not available at the time of this writing but will be (have been) presented at the Stanford Geothermal Workshop, January 30 through February 2, 2012. Please contact the primary author at the email above for a copy of the presentation and results.

REFERENCES

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

Entingh, D. J., G. L. Mines, et al. (2006). DOE Geothermal Electricity Technology Evaluation Model (GETEM): Volume I - Technical Reference Manual. Washington DC, US Department of Energy, Office of Energy Efficiency and Renewable Energy.

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

Helton, J., C. (1994). "Treatment of uncertainty in performance assessments for complex systems." Risk Analysis **14**(4): 483-511.

Lowry, T. S., V. C. Tidwell, et al. (2010). "A Multi-Tiered System Dynamics Approach for Geothermal Systems Analysis and Evaluation." GRC Transactions **34**: 85-90.

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.