

A Probabilistic Assessment of Enhanced Geothermal Systems, Uncertainty, and Levelized Cost of Electricity

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ABSTRACT

This work uses the coupled performance between an EGS reservoir and a binary power plant to determine the probability of meeting a target levelized cost of electricity (LCOE) as a function of the combined uncertainties in reservoir and power plant performance and capital and operating and maintenance (O&M) costs. Our motivation lies in answering the question, 'What combinations of reservoir and power plant performance and capital and O&M costs allow us to hit a target LCOE?'. This question is the inverse to what is usually addressed (i.e., what is the LCOE for a given set of inputs?) and allows us to better rank the factors that influence LCOE the most and provide insight with regards to where performance and/or cost cutting efforts should be focused. Using the integrated geothermal systems model, GT-Mod, a hypothetical system is created that uses 5 injection wells, 10 production wells, an initial reservoir temperature of 180 °C, and a target power sales of 25 MW as the basis for the analysis. Working fluid mass flow rates are varied as a function of the brine input temperature to insure the plant is maintaining the proper thermodynamic targets.

Uncertainty in reservoir drawdown is represented by randomly changing reservoir parameters over realistic ranges. Default capital and O&M costs are calculated in GETEM and then varied across plausible ranges using exponentially distributed random variables. Capital and O&M costs are refined into four sub-categories each; exploration and confirmation, well costs, plant costs, and makeup and other costs. Results are presented as a set of probability plots that show the performance and economic conditions that must exist to reach different LCOE targets.

1. INTRODUCTION

This work uses the coupled performance between an EGS reservoir and a binary power plant to determine the probability of meeting a target levelized cost of electricity (LCOE) as a function of the combined uncertainties in reservoir and power plant performance and capital and operating and maintenance (O&M) costs. Our motivation lies in answering the question, 'What combinations of reservoir and power plant performance and capital and O&M costs allow us to hit a target LCOE?'. The purpose is to explore the set of parameters that meet or exceed the target LCOE's and to better rank the factors with the greatest influence on the LCOE and provide insight with regards to where performance and/or cost cutting efforts should be focused. The analysis is based on probabilistic simulations using GT-Mod (Lowry et al., 2010) that begins with an assumed reservoir and plant configuration and then varies uncertain parameters based on probability distribution functions.

This approach is the inverse of typical EGS economic analyses that attempt to determine the LCOE for a given set of input parameters. It assumes that uncertainties in EGS energy development are an inherent piece of the process that should be considered in any physical and/or economic analysis of a system. EGS is unique in that it operates as a closed loop that can enhance and augment any feedbacks within the system and that can have a large impact on system performance. A simple example is the feedback between plant and cooling efficiencies and thermal drawdown; plant and cooling efficiencies affect the injection temperature of the brine, which in turn affects the thermal drawdown in the reservoir, which in turn affects the plant performance. The importance of these feedbacks stems from the fact that uncertainties in any one parameter can be augmented, diminished, or irrelevant based on the dynamic relationship between that parameter and the rest of the system.

We use the Gringarten solution method in GT-Mod to calculate thermal drawdown (Gringarten, et al., 1975). The Gringarten solution is an analytical solution to heat transfer in fractured media that assumes parallel fractures and thus can account for variability in the number of fractures (which controls the volume of brine through each fracture) and the fracture aperture (which controls the velocity of the brine through each fracture). These two parameters (number of fractures and fracture aperture) are discussed in more detail below.

2. SETUP

The analysis assumes a resource depth of 2500 m with an initial temperature of 180 °C. The plant size is set to produce 25 MW in power sales at the start of the simulation. The plant model is a simple water-cooled binary system using isopentane as the working fluid. The brine mass flow rate is set at the start of the simulation using the target power sales of 25 MW and a pumping overhead of 1 MW and is held constant throughout the simulation and the working fluid mass flow rate is varied as the brine inlet temperature changes, which has the effect of reducing power production as the reservoir cools. There are 10 production wells, which is determined by dividing the total brine mass flow rate by a defined mass flow rate limit per production well, which is set at 50 kg/s and which was determined through trial and error to produce a reasonable amount of headloss in the wells and across the reservoir. The number of injection wells (5) is based on an injection to production well ratio of 0.5. The project implementation assumes that the plant size and working fluid mass

flow rate are controlled by the initial temperature and the brine mass flow rate. This follow conventional processes whereby a power plant is not designed and built until one knows the production temperature and brine mass flow rates that are attainable.

Production and injection well costs are calculated a priori using GETEM (Entingh, 2007) and are set as constants in the model at \$9,295,048 and \$11,868,686 ea., respectively. In addition, three exploration wells and three confirmation wells are assumed to be drilled as part of the exploration and confirmation process, with the confirmation wells being used as production wells. The cost of the confirmation wells is 1.2 times that of a production well (\$11,154,058) and the cost of the exploration wells is set at \$5,905,380. Both these values stem from the default settings in GETEM. The current version of GT-Mod (v3.1.0) calculates the balance of the capital costs and all the O&M costs internally using a regression against the cost calculations in GETEM to allow for a direct calculation of the LCOE within GT-Mod. The key input parameters, including those controlling plant performance are listed in Table 1..

Table 1 - Listing of key input parameters.

Parameter	Value	Parameter	Value
Depth	2500 m	Target Power Sales	25 MW
# of Production Wells (incl. confirmation wells)	10	Well Separation Distance	500 m
# of Injection Wells	5	Screened Interval	500 m
# of Confirmation and Exploration Wells	3 ea.	Pre-heater/Evaporator Pinch Point	5 C
Production Well Cost	\$9,295,048	Evaporator Pressure	1 MPa
Injection Well Cost	\$11,868,686	Condenser Temperature	40 C
Confirmation Well Cost	\$11,154,058	Turbine Efficiency	85%
Exploration Well Cost	\$5,905,380	Feedpump Efficiency	75%
Resource Temperature	180 C	Project Lifetime	30 yrs
Total Brine Mass Flow Rate	~452.0 kg/s		

3. UNCERTAINTY

Uncertainty in the costs are represented using multipliers defined by exponential probability distribution functions (PDF's) that are applied to the well field and power plant capital costs. The distribution parameters are set to keep the multiplier under 7% (i.e., a value of 1.07) 50% of the time, and under 23% (i.e., a value of 1.23), 90% of the time (Figure 1). This mimics the uncertainty between the actual costs (i.e., what one actually pays) and the cost curve calculations used in GETEM from which the initial values are derived.

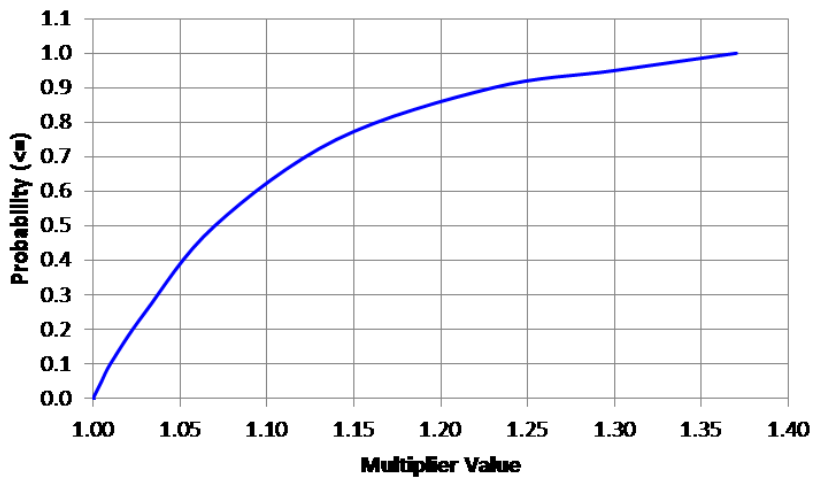


Figure 1 - Cumulative distribution plot of the cost multipliers random variable.

The reservoir height is set equal to the screened interval of the wells (500 m) and its length is set by the separation distance between the production and injection wells (500 m). The reservoir width describes the amount of reservoir material that is accessed between the production and injection wells and is assumed to range between 400 and 800 m using a uniform PDF. Like the number of fractures, the reservoir width controls the brine volume through each unit width of fracture, which is a required input to the Gringarten solution.

While most the literature agrees that fracture aperture is best described using a lognormal distribution (e.g. Bertels, 2001), we also wanted to maintain a loose correlation between it and the number of fractures. The assumption is that a reservoir will be stimulated to a target intrinsic permeability of $5.0\text{e-}15 \text{ m}^2$ with some variability around that number due to the number of fractures and the aperture. For a low number of fractures, the aperture needs to be larger than if there are a large number of fractures. To achieve this, the aperture is calculated using the following equation, which is based on Snow (1968):

$$a = \sqrt[3]{\frac{6k_a H}{n_{frac}}} \quad (1)$$

where a is the aperture [m], k_a is the assigned permeability [m^2], H is the height of the reservoir, and n_{frac} is the number of fractures. The assigned permeability, k_a , is varied by taking the exponent of the product of a uniformly distributed random variable that varies between 0.95 and 1.04 and the natural logarithm of the target permeability as follows:

$$k_a = \exp(\ln(k_{targ}) v_k) \quad (2)$$

where k_{targ} is the target permeability and v_k is the random variable.

The number of fractures are randomized using a lognormal distribution with an expected value of 2.47 and a standard deviation of 0.78. The distribution parameters are based on the number of fractures needed as a function of reservoir width to have the reservoir end temperature reach the plant design temperature of 164.7 C, with the other random variables held constant at their means. A cumulative distribution function was fitted to the data points and the distribution parameters were calculated.

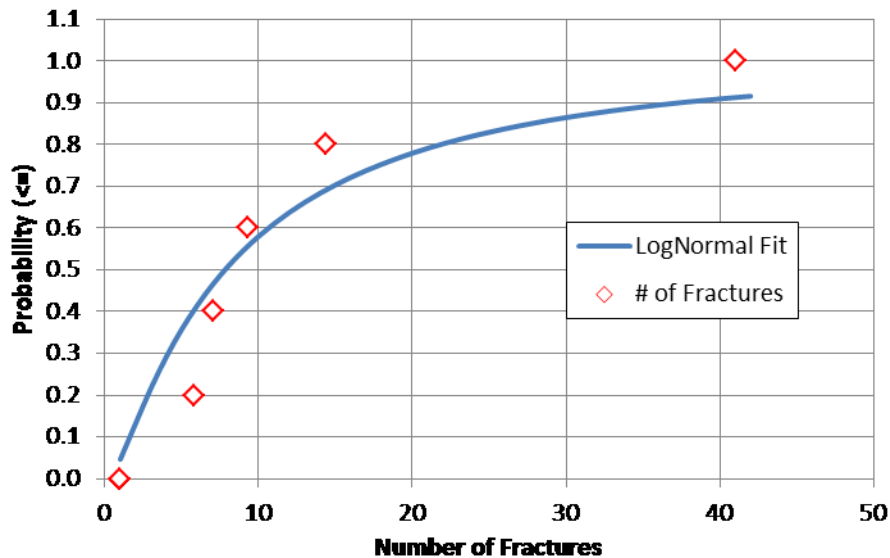


Figure 2 - The cumulative distribution function for the number of fractures needed for the reservoir end temperature to equal the plant design temperature of 164.7 C.

4. RESULTS

Figure 3 shows the cumulative distribution of the LCOE over the full range of uncertainties. The plot shows that there is a 10% probability that the LCOE will be less than or equal to 16.71 $\text{\$/kW-hr}$ and a 50% probability that it will be less than or equal to 26.57 $\text{\$/kW-hr}$. The fact that the maximum probability tops out at 76% is because the remaining 24% of the simulations have ending production temperatures that are below the minimum plant temperature and thus the project is considered to have failed. Rather than assign an arbitrary value to the LCOE for these runs, they are eliminated from the numerical analysis but are used to shift the curves accordingly.

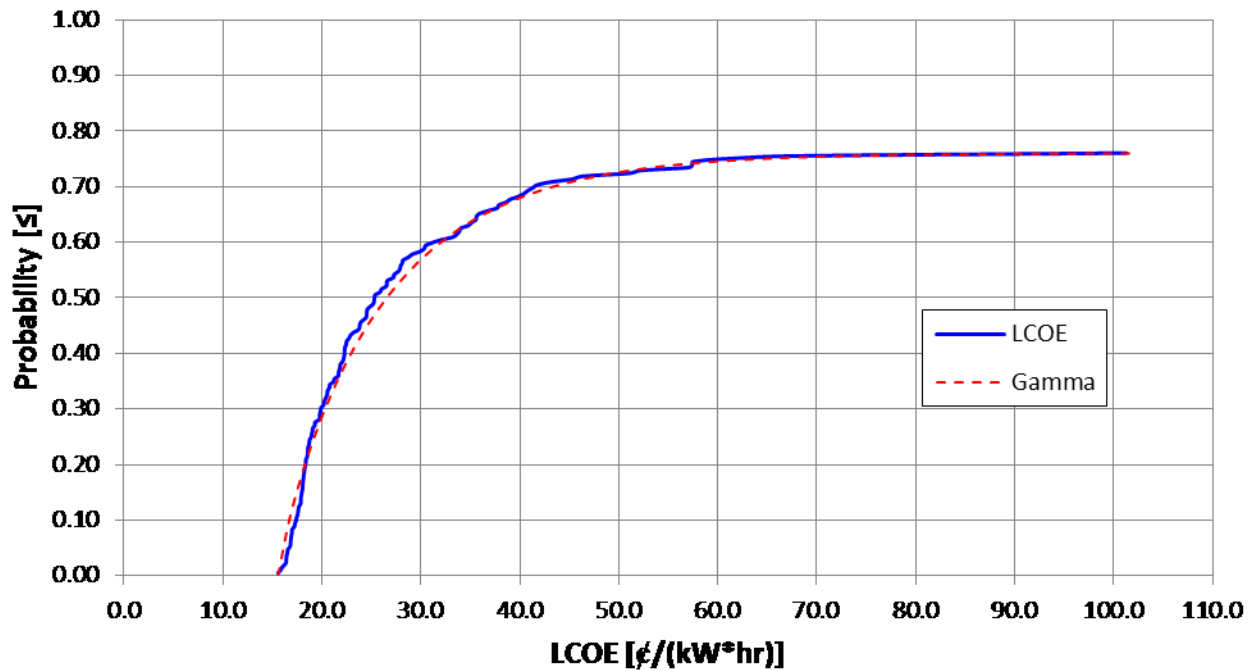


Figure 3 - Cumulative distribution of the LCOE over the full range of uncertainties. The maximum probability pertains to the simulations when the minimum reservoir temperature did not drop below the minimum allowable plant temperature. The gamma fit is included as a point of reference.

In addition to capital and operations and maintenance costs, the LCOE is also a function of the power sales. Power sales can change over the life of the project due to a decline in the brine production temperature and/or an increase in pumping requirements. Figure 4 shows the probability of averaging a given level of power sales over the life of the project. The figure shows that there is a 50% probability that the average power sales will be less than or equal to 21.3 MW. Like the LCOE the curve is shifted due to the failed simulations but in this case, the curve is shifted upwards.

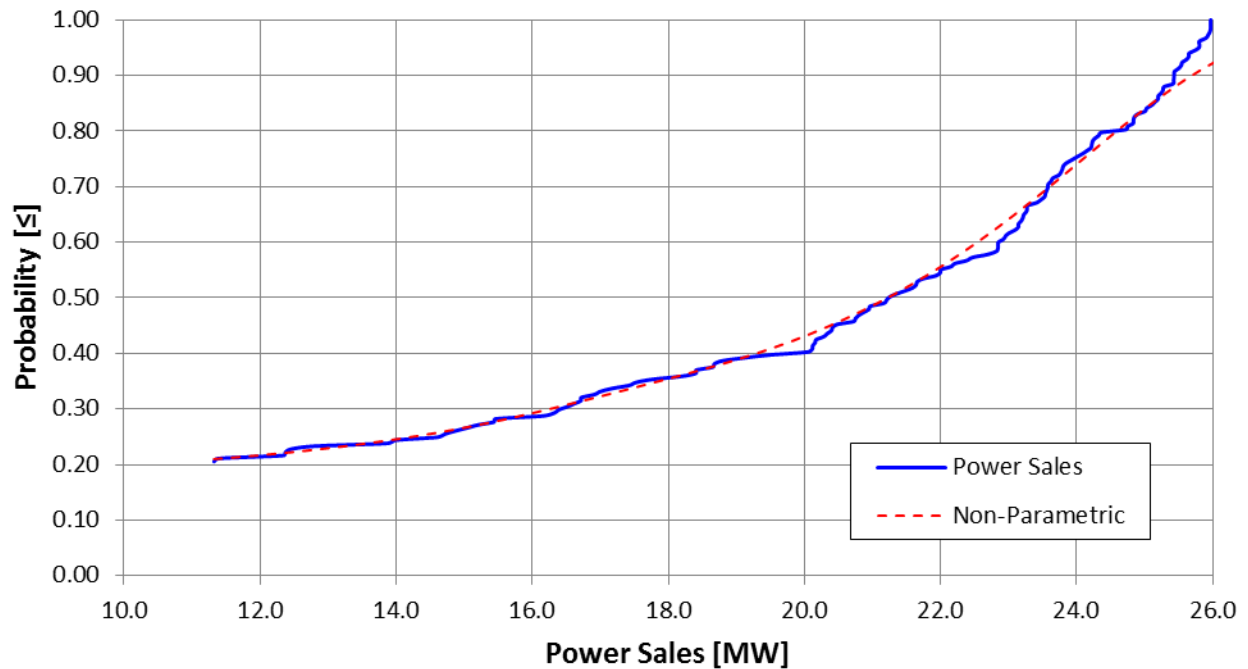


Figure 4 - Cumulative distribution of the average power sales over the full range of uncertainties. The non-parametric fit is included as a point of reference.

Figure 5 shows the components of the LCOE at the minimum (Q0), 25th (Q1), 50th (Q2), 75th (Q3) and 100th (Q4) percentiles. Table 2 lists the numerical values for the plot in Figure 6. It is easy to see that the capital costs associated with well drilling is by far the greatest contributor to the LCOE. What is interesting to note is that there is general correlation between the LCOE and the percentage of the well capital costs. In other words, reducing the well capital costs has the largest impact on the LCOE.

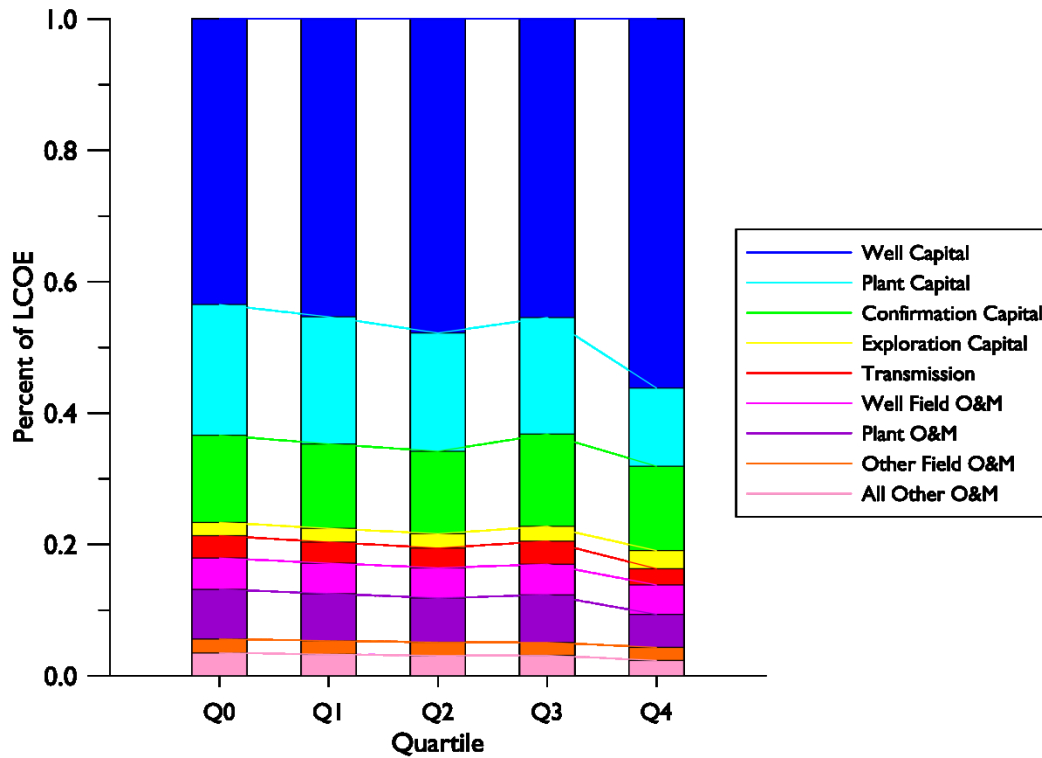


Figure 5 - The components of the LCOE at the minimum (Q0), 25th (Q1), 50th (Q2), 75th (Q3) and 100th (Q4) percentiles.

Table 2 - Components of the LCOE and their percentage of the total LCOE at different statistical breakpoints.

Component	Minimum	25 th Percentile	50 th Percentile	75 th Percentile	100 th Percentile
Well Capital	0.435	0.453	0.478	0.455	0.562
Plant Capital	0.199	0.194	0.180	0.177	0.119
Confirmation	0.133	0.128	0.126	0.140	0.128
Exploration	0.020	0.021	0.022	0.023	0.028
Transmission	0.034	0.032	0.030	0.035	0.025
Well Field O&M	0.048	0.046	0.046	0.047	0.045
Plant O&M	0.076	0.072	0.067	0.073	0.050
Other Field O&M	0.021	0.021	0.020	0.020	0.020
All Other O&M	0.035	0.033	0.031	0.031	0.023

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