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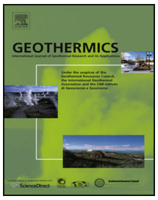

Uncertainty analysis of geothermal well drilling and completion costs

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ABSTRACT

The goal of this study was to characterize the uncertainty associated with the cost of drilling and completion of geothermal wells. Previous research and publications have produced correlations for the average cost of geothermal wells as a function of well depth. This project develops this concept further by using a probabilistic approach to evaluate the distribution of geothermal well costs for a range of well depths. The well cost uncertainty was characterized by identifying the main cost components of geothermal wells and quantifying the probability distributions of the key variables controlling these costs. These probability distributions were determined based on the detailed cost records of U.S. geothermal wells drilled or designed from 2009 to 2013 as well as cost data from drilling equipment manufacturers and vendors. Probability distributions of the key variables were examined to find statistically significant correlations between them. Lastly, the previously determined probability distributions of individual cost components and the correlations between them were input into WellCost Lite, a predictive geothermal drilling cost model, using the Monte Carlo method. This approach allowed us to generate the overall well cost probability distributions for 8000–15,000 ft. (2400–4600 m) geothermal wells. We have shown that the median geothermal well cost increases exponentially with depth. Deep wells typically have higher cost uncertainty and more positively-skewed cost probability distributions. The correlations presented in this paper can be used to determine the economic feasibility of geothermal energy systems, assess the project risk, and facilitate investment decisions.

1. Introduction

U.S. electricity demand is growing due to the increasing population and ongoing electrification of end-use consumption. The total energy demand in residential and commercial sectors has also increased by 0.5% per year since 2000 despite energy conservation measures (EIA, 2015). In order to meet this growing demand while working towards carbon emissions reduction, the U.S. will need to invest in low-carbon energy technologies. While solar and wind energy will both likely play a large role in meeting the growing demand for renewable electricity, these resources are both intermittent throughout the day and seasonally and cannot provide consistent base-load power without large-scale energy storage. Geothermal energy, and specifically Enhanced Geothermal Systems (EGS), offer a potentially promising solution for the U.S. as a clean, renewable, base-load energy source (Gerber and Marechal, 2012). Despite its high potential (Tester et al., 2006), geothermal energy development in the U.S. has been relatively slow, with electric output increasing by only 2.8% per year between 2008 and 2014 (GEA, 2014). This slow growth was primarily due to low cost of natural gas, large capital investment required by geothermal projects, and the shortage of favorable policies. Another cause of slow implementation was the industry's focus on electricity generation from shallow, high-grade hydrothermal resources, which are limited in availability and found mainly in the Western U.S. (Tester et al., 2015, 2006). This narrow focus overlooks the potential for providing heat for direct-use and cogeneration applications from low- and medium-grade geothermal resources. Direct-use applications are not affected by the low heat-to-power conversion efficiencies and could be economically implemented almost anywhere in the U.S. (Beckers et al., 2014; Reber et al., 2014).

Enhanced Geothermal Systems (EGS) are created using hydraulic stimulation to extract thermal energy from hot subsurface rocks that lack sufficient permeability and/or in situ fluid.

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One of the primary obstacles in developing deep EGS resources is the cost and uncertainty associated with drilling deeper wells. For low-grade EGS wells, drilling expenditures can account for more than 60–75% of total project costs (Petty et al., 2009; Tester et al., 2006). The uncertainty of well costs is also expected to increase with well depth due to more trouble time, higher formation temperatures and pressures, and increasingly complex well designs. Gaining an understanding of the drilling cost uncertainty could help geothermal developers in securing low-interest financing by reducing the infrastructure risks. Therefore, characterization of geothermal well drilling costs and uncertainty are critical to the growth and expansion of geothermal development, particularly for lower-grade, deeper resources.

Geothermal well costs have been evaluated as a function of depth by a number of authors (Augustine et al., 2006; Lukawski et al., 2014; Mansure and Blankenship, 2013; Tester et al., 2006). The study by (Augustine et al., 2006) introduced the MIT Depth Dependent (MITDD) well cost index based on tens of thousands of hydrocarbon wells drilled each year between 1976 and 2003. MITDD index was used to express the historical costs of geothermal wells in 2003 U.S. dollars. This allowed the authors to compare the costs of geothermal wells drilled at different times and create a cost vs. depth correlation in 2003 U.S. dollars. The work on MITDD index by (Augustine et al., 2006) was updated and extended by (Lukawski et al., 2014). The authors proved that the recent cost escalation rates of geothermal wells have been lower than those of oil and gas wells, and that a cost index based on hydrocarbon wells is no longer applicable to geothermal well drilling. As a result, the geothermal well cost correlation in (Lukawski et al., 2014) was based on 42 geothermal wells drilled or designed between 2008 and 2013. While both studies provide predictions for the average costs of geothermal and hydrocarbon wells at depths ranging from 3000 to 30,000 ft. (910–9100 m), they do not characterize the range of uncertainty around these average costs. Both studies point to the limited availability of geothermal drilling data as the reason for taking this deterministic approach.

The first publication to consider uncertainty as part of the EGS well costing calculation was (Yost et al., 2015). The authors used a computer program called Decision Aids for Tunneling (DAT) to model distributions of costs and times associated with each step of well drilling and completion. The overall cost of each drilling or completion activity was represented as a function of a fixed material cost, an hourly cost, and a time required for that activity. Uncertainty was factored into these equations by inputting probability distributions for all costs and times, which were obtained from the Sandia geothermal well database (Polsky et al., 2008). This yielded a method for calculating overall well cost probability distribution. However, the analysis by (Yost et al., 2015) is based on one EGS well and does not account for non-productive time (NPT). It also assumes that individual well cost components are not correlated with each other. This assumption may not always be valid; e.g. volumes of drilling mud and cement are often correlated since they are both affected by the frequency and severity of circulation loss events.

Our approach builds upon past methodologies to quantify the cost uncertainty of 8000–15,000 ft. (2400–4600 m) deep EGS wells located in the U.S. While these depths may seem low compared to the previous well cost analyses (Augustine et al., 2006; Lukawski et al., 2014), approximately 70% of EGS wells drilled in the past fall within this range (Breede et al., 2013). Compared to the previous studies (Augustine et al., 2006; Lukawski et al., 2014; Mansure and Blankenship, 2008), this work presents probability distributions of well costs instead of a single, average drilling cost. Our work builds on the probabilistic approach introduced by (Yost et al., 2015) by accounting for the non-productive time, including the correlations between individual well cost components, and most importantly by analyzing a range of EGS well depths instead of a single 20,000 ft. (6100 m) well.

Correlations presented in this paper can be used to determine the cost probability distributions for wells of any measured depth (MD) within the 8000–15,000 ft. (2400–4600 m) range, assess the project risk, and facilitate investment decisions. To enhance the accuracy of our data set, we incorporated only the most recent well cost data from the U.S. geothermal industry, from the period of 2009–2013. Our well cost database includes fourteen hydrothermal wells drilled in the Western U.S. in similar geologic conditions, EGS wells from previous publications (Baker Hughes, 2012), and EGS wells designed in WellCost Lite for the purpose of this study. The well cost records were analyzed to: 1) determine the main variables influencing the costs of drilling and completing geothermal wells, 2) obtain the probability distribution of each of these variables, and 3) identify significant correlations between these variables. These distributions and correlations were then input to WellCost Lite, a predictive drilling cost model, using Monte Carlo method to obtain the probability distribution for the overall well cost as a function of depth.

The geothermal wells analyzed in this work were drilled in or designed for locations in the United States. Consequently, our analysis uses U.S. drilling, labor, and material costs. As a result of the limited access to detailed drilling cost data for recently completed geothermal wells, our database contains wells drilled in various locations. This introduces an additional scatter to the well cost database due to the differences in formation lithology and various location-specific costs such as rig rates. However, while the cost differences between individual geothermal fields are important, accounting for them reduces the overall cost variability by only 11% (Mansure et al., 2006). With a more extensive well cost database, presented methodology could also be used to produce more accurate correlations for individual geologic provinces.

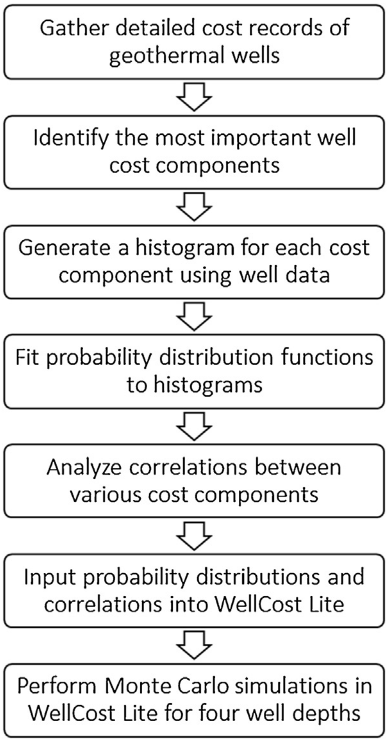

Fig. 1. Flowchart representing the used methodology.