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A Stochastic Economic Analysis of An Enhanced Geothermal System

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ABSTRACT

This paper presents a stochastic economic analysis of an Enhanced Geothermal System (EGS) in terms of the customary yardsticks of Net Present Value, Return on Investment, etc. The analysis includes the distribution of outcomes for the yardsticks and the sensitivity of the investment relative to the importance of each factor. The results are therefore subject to the uncertainty introduced in the form of probabilistic distributions.

A financial model used to evaluate the economic benefits of a traditional oil & gas development was converted to one that could be applied to a power plant running off an EGS heat exchanger. This model was used to provide a deterministic model basis for the stochastic modeling needed to quantify the impacts of input uncertainties of variables associated with an EGS development. This allows a sensitivity analysis to determine the relative impact of the various factors such as well costs, initial fluid flow and decline rate, OPEX, pricing, etc. on the ultimate economic returns. The most important factor in the EGS economics is the initial power capacity of the system, which is driven by deliverability of the induced fractures and the total heat exchange drainage volume (HEDV). The second factor is the decline rate of the system power generation over time. The power generation decline rate is driven by the conformance control of circulating water in the system and the avoidance of water short-circuiting, which would result in premature cooling of water delivered to the power plant. First, this paper examines the relative effects of the initial system production rates, decline rates, development efficiency, and price variability on the financial metrics of an EGS project. Second, the paper illustrates the usage of a stochastic model to determine the development path for an EGS project and the relative contributions of the various factors on the project economics.

1. Introduction

Enhanced Geothermal Systems (EGS) are systems that inject water into wells that create subsurface heat exchangers. The water then travels through the reservoir and harvests heat from the hot rock. The resulting hot water is brought to the surface through a production well. This paper examines the economics associated with the development of EGS using stochastic methods. Until FERVO Energy's recent EGS pilot in Nevada, multi-stage stimulation techniques in horizontal wells have been applied successfully to reduce costs in unconventional oil and gas wells, but not in geothermal wells. This is due to temperature limitations and casing size limitations. An EGS system of two or more horizontal wells that are connected by fractures, is depicted in Figure 1.

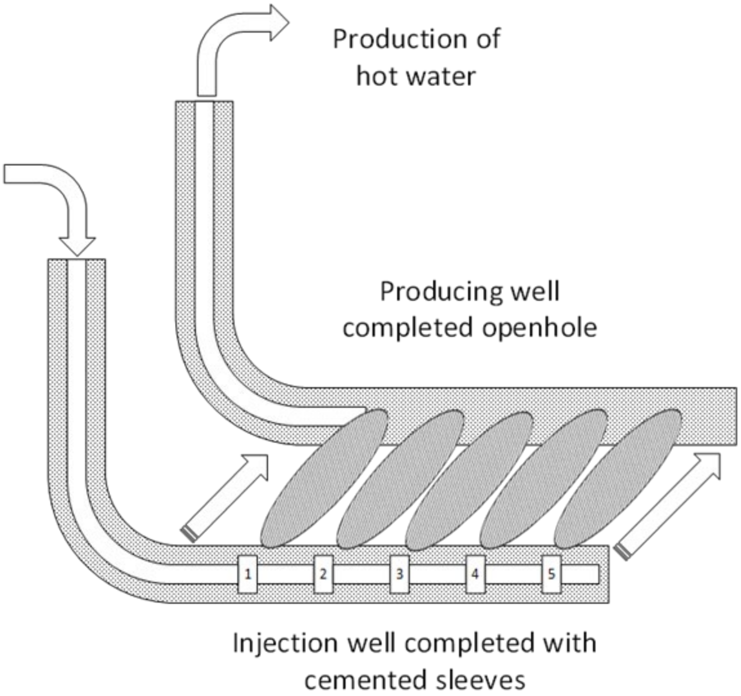


Figure 1: GeoThermOPTIMAL (Fleckenstein et al. 2021)

In EGS, at least two wells will be connected through several networks of both induced and natural fractures. In EGS reservoirs with little natural fracturing, most heat exchange would need to be accomplished through the induced fractures, so to achieve the required flow rates for an economic EGS project, the multistage fracturing method must be rapid and inexpensive. The horizontal injectors and producers must then be used for long term production with conformance control to optimize the heat recovery. The system design parameters are dependent on the size of the subsurface heat exchanger that is created, the temperature of the resource rock, and the heat exchange rates achieved in the system with required rates of 125 l/s or 68,000 BWPD per well. These rates are a typical per-well generation capacity in the hydrothermal industry and are a good benchmark for an EGS project in today's market (Olson, 2015).

The system performance must be maintained with acceptable heat recovery for 20-30 years. To achieve these long-term rates and heat recovery, the heat exchange drainage volume (HEDV) of the reservoir must be considerably larger than those in previous EGS projects. Previous EGS systems prior to the FERVO wells drilled in Nevada in 2023 were vertical or directional wells, which necessarily have smaller areal drainage and injection and production footprints per well.

For example, the Los Alamos Hot Dry Rock EGS system used directional injecting and producing wells, with fingering of injection water in a relatively small, fractured volume between them. The HEDV of the EGS reservoir can be increased using approximately parallel horizontal wells linked with multiple fractures. This creates more induced fracture networks between horizontal wells with multistage fracturing techniques or may access larger volumes of natural fractures or porosity systems. However, the "short-circuiting" phenomenon must be avoided.

To prevent the fluid from short circuiting between the injector and producer wells, flow and temperature needs to be detected and diverted to ensure that the heat is harvested from the entire volume of hot rock. This minimizes thermal decline in the produced water and maintains the rates and fluid temperatures needed for the electrical generation plant. Additional hot fluid can be added to the system with a natural gas heated system, such as a binary power plant used in co-generation electrical generation plants, to provide sufficient additional heat and overcome the normal decline in heated water production from an EGS project. A somewhat similar system was used by FutEra Power Corp at Swan Hills, Alberta, and is expected to have a capacity of up to 21 megawatts. At least 25 per cent of this capacity will be from geothermal heat and waste heat recovery. The combination of geothermal heat with other heat will increase the carbon emission of a single EGS system but lower the overall unit emissions for the power generated and increase the cost competitiveness of the EGS system, particularly as experience is gained and cost and resource optimizations occur. This could accelerate the system adoption and speed up the energy transition.

2. Enhanced Geothermal Systems (EGS) History

Enhanced Geothermal Systems evolved from the hot dry rock concept (HDR) project implemented by Los Alamos National Lab at Fenton Hill in 1977. The results demonstrated that heat could be extracted from a hydraulically stimulated region of low-permeability hot crystalline rock. The history of EGS is chronicled, with a thorough list of references, in the paper "Enhanced Geothermal Systems (EGS): A Review" (P. Olasolo, 2016). Unlike conventional geothermal reservoirs that are dominated by hydrothermal convective heat transport, the HDR concept is dominated by conduction only. The strategy of EGS has evolved to the creation of subsurface geothermal reservoirs in practically impermeable hot granitoid rock. This reservoir would be created by inducing hydraulic fractures and opening pre-existing natural fractures and fissures resulting in a subsurface heat exchanger. Water or other liquids with lower boiling points could be used as an injectant into the subsurface fracture network, to extract thermal energy from the surrounding rock. Hot water would be produced to generate electrical power at the power plant.

Multi-stage fracturing of horizontal wells for geothermal completions has been described in several publications (Eustes et. al, 2018) and is a well-known concept. A review of previous attempts to use shale development techniques in EGS can be found in "Review of Recent Unconventional Completion Innovations and their Applicability to EGS Wells" (Gradl et al. 2018). More recently, a paper by Guinot and Meier, 2019, described the unsuccessful efforts to develop an EGS at the Basel Deep Heat Mining (DHM) project, and reviewed concerns over induced seismicity, as well as multi-stage stimulation in the oil and gas industry and its applicability to future EGS projects. Several EGS projects have been commercially operating; Soultz (1987-present) in France, Landau (2004-present) and Insheim (2008-present) in Germany, and the Pohang Project in South Korea. These projects are limited by the HEDV possible by using vertical or directional injection and production wells, which was a similar limitation to shale development.

Shale development was only economic when long horizontal wells were completed with multi-stage hydraulic fracturing to increase the Stimulated Reservoir Volume, or SRV, an analogy to an EGS HEDV. This is a key to better EGS economics.

3. Conformance Control and GeoThermOPTIMAL System

High rates of fluid injection into single fractures cools the produced water quickly since the heat transfer cannot keep up – “short-circuiting” as depicted below (Fleckenstein, 2022). Ideally one would like to limit each fracture to 1,000 – 2,500 BWPD, which requires many individual fractures connecting injectors to producers and a means to control the fluid movement.

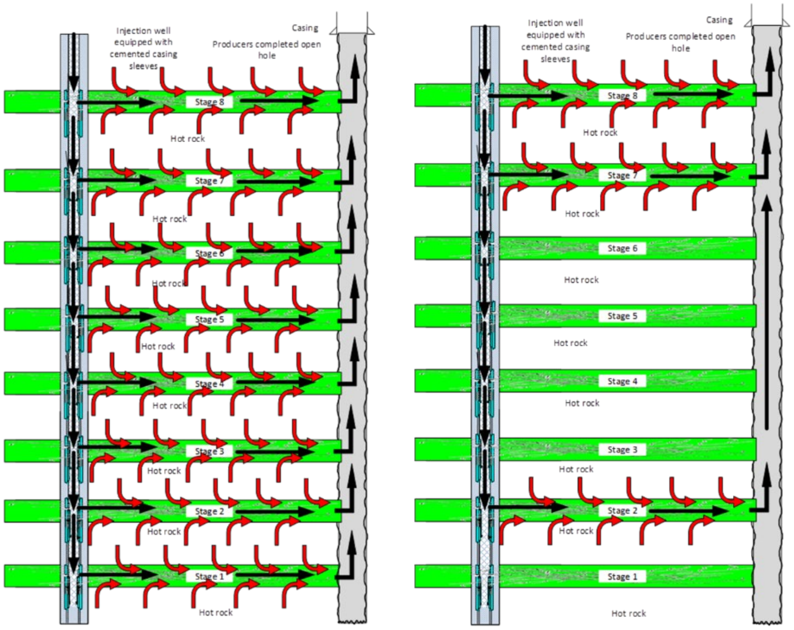


Figure 2: EGS Conformance Control (Fleckenstein, 2022)

This flow conformance must overcome variability in fracture conductivity by the deployment of a conformance control system similar to the GeoThermOPTIMAL system that has been previously described (Fleckenstein 2021) and is being developed as part of the DOE funded Utah FORGE program. Conformance control methods close off or use back pressure to accomplish a uniform injection profile along the length of the injection well. Oilfield waterfloods have experience with conformance control (Smith, 2023). GeoThermOPTIMAL uses “next generation” multi-purpose sleeves, and single sized, large dissolvable balls during multi-stage stimulation operations. The cement encapsulates the casing and the sleeves for annular isolation allowing thermal axial stresses to be resisted by the cement sheath.

A tractor using modular capabilities to allow various tools and sensor packages to be attached for flow conformance control is being built and tested. The original hydraulic tractor concept using coiled tubing was replaced with an electric wireline tractor design to improve operating costs. To address the wellbore conditions reaching 225°C, an innovative flask design was devised to protect the critical electronic components. This design eliminates the requirement for water circulation to cool the electronics. The high-temperature tractor is based on an electric wireline design that incorporates a fluid survey capability for the detection of fluid injection and production, allowing for the precise opening or closing of the sleeve to achieve conformance control. It is contemplated that future tools are expected to incorporate a feature that enables choking of fluid flow through the sleeve, regardless of the conductivity of the fracture. The sleeve and tractor are currently undergoing final development and testing at 225°C, which would provide a TRL-6. The field demonstration at FORGE in the summer of 2024 would result in a TRL-8.

4. EGS Prior Economic Models

Stochastic and deterministic economic models have been developed for EGS. In deterministic models, the output of the model is "determined" by the single values chosen for each variable in a series of equations. Stochastic modeling uses random sampling of parameters or inputs to explore the behavior of a complex system or process. Stochastic modeling, sometimes called "Monte Carlo Simulation" quantifies the uncertainty in a model by converting single value independent variables to distributions, with values chosen for that variable by the random, weighted sampling of distributions. These models will lead to an ensemble of different output ranges and can quantify the impact of changes in various factors and allow optimization for investments needed to effect these changes. A benefit of stochastic modeling is the quantification of the relative impacts of various individual factors in discounted cash flow models that influence the project economics.

The concept of Levelized Cost of Energy (LCOE) measures lifetime costs which are divided by energy production. In its simplest form, LCOE gives a metric that allows the comparison of the capital costs, O&M, performance and fuel costs of a power plant. This calculates the present value total cost of building and operating a power plant. The LCOE allows a calculation of the minimum price of energy for an energy project to achieve a given economic metric. The use of LCOE allows the cost comparison of different energy generation technologies such as wind, solar, natural gas etc, of unequal life spans, different project sizes, capital costs, risk, and varying capacities. LCOE comparisons are useful to the comparison of the value of a project in a portfolio approach.

The Geothermal Electric Technology Evaluation Model (GETEM) was originally developed for the Department of Energy's Geothermal Technologies Program (GTP) as an Excel-based tool for estimating the levelized cost of energy for definable geothermal scenarios. GETEM provides both a method for quantifying the power generation cost from geothermal energy, and a means of assessing how technological advances might impact those generation costs. Electrical power generation is the sole geothermal use considered by GETEM and can evaluate either conventional hydrothermal or EGS system using either a flash-steam or binary power plant.

GEOPHIRES (Beckers et al. 2013, 2014) is an economic model that simulates the subsurface reservoir, wellbore, and surface plant with either internally defined or user defined models. GEOPHIRES, resulted from models developed after the Fenton Hill Hot Dry Rock (HDR) project at Los Alamos National Laboratory (Tester et al. 1979) culminating in the HDR Model described in "Heat Mining" by Armstead and Tester (1987). This model became the MIT-HDR model (Tester and Herzog 1990), and in the 1990s, that model evolved into the MIT-EGS model (Tester et al. 2006). Beckers and others at Cornell University developed GEOPHIRES, which provides estimates of the reservoir production temperature and provides surface plant direct heat and/or electricity production. GEOPHIRES applies levelized cost models to relate investment and levelized cost of electricity and/or heat (LCOE and LCOH).

The BICYCLE Levelized Life Cycle Cost model was developed at Los Alamos National Laboratory (Hardie 1981). It allows for accounting for variable debt/equity return rates, a variety of tax rates, and accounts for an investment tax credit.

Each of these models have taken into consideration a variety of variables and assumptions, linking the reservoir performance to economic performance, and some have included stochastics elements in the models or analysis.

5. Proposed Stochastic Model of EGS

An examination of the models described above can provide insights and a foundation for building a useful stochastic model needed to make technology decisions when designing an EGS project. Since EGS development is experimental in nature, these design decisions will come with varying amounts of uncertainty. Hence, a stochastic economic model is presented which allows the evaluation of design choices using probabilistically distributed variables to see a range of possible outcomes. This allows for decision-making under uncertainty: a key step for companies that are considering taking on such a project. As technology continues to develop, understanding the economic risks and rewards of design variables is key for EGS to be economically implemented.

Well construction and economies of scale improvements reflecting those in shale development were incorporated in the analysis to examine EGS economics under similar conditions. Drilling cost estimates were made with modifications of an existing model (Finger, J. 2023) that allows for an examination of cost differentials with changes in drilling performance and design. This allowed the assessment of the impact on the EGS economics of changes in economic parameters, such as improved rate of penetration (ROP) with polycrystalline diamond compact PDC bits and mechanical specific energy (MSE) techniques, but also changes in well construction design, such as the use of monobores and open hole completions. It is important to note that both drilling, and completions costs are also highly dependent on availability of oil field service company equipment with the resultant cost efficiencies of the equipment that can be used for both geothermal and oilfield development, such as drilling rigs and stimulation equipment.

5.1 Model cost estimates

Estimates of costs were made based on estimates for the historical improvements in shale development wells. As horizontal shale drilling has become better understood and researched, adjustments in drilling and completions strategies have been implemented to improve profitability. Although drilling and stimulating longer laterals incurs larger upfront cost, the economic benefit has been proven in the oil and gas industry. Figure 3 below shows the history of one operator’s total well cost vs. estimated ultimate hydrocarbon recovery in the Bakken/Three Forks (R. Rankin et al, 2010). As the length of the lateral sections was extended with the incorporation of more frac intervals, the total well cost increased dramatically. However, the project economics and the estimated ultimate recovery significantly increased with longer laterals and more fracture stages. As seen below, a well with a 4500’ shorter lateral will still produce more hydrocarbons if completed with more frac stages, as the induced fractures contact a much larger volume of reservoir rock than the wellbore itself. Improvements in EGS economics follow a similar trend. Similar step change improvements are seen in drilling rates at FORGE with instantaneous ROP increased over 400% and footage per bit was increased over 200% (Dupriest 2022).

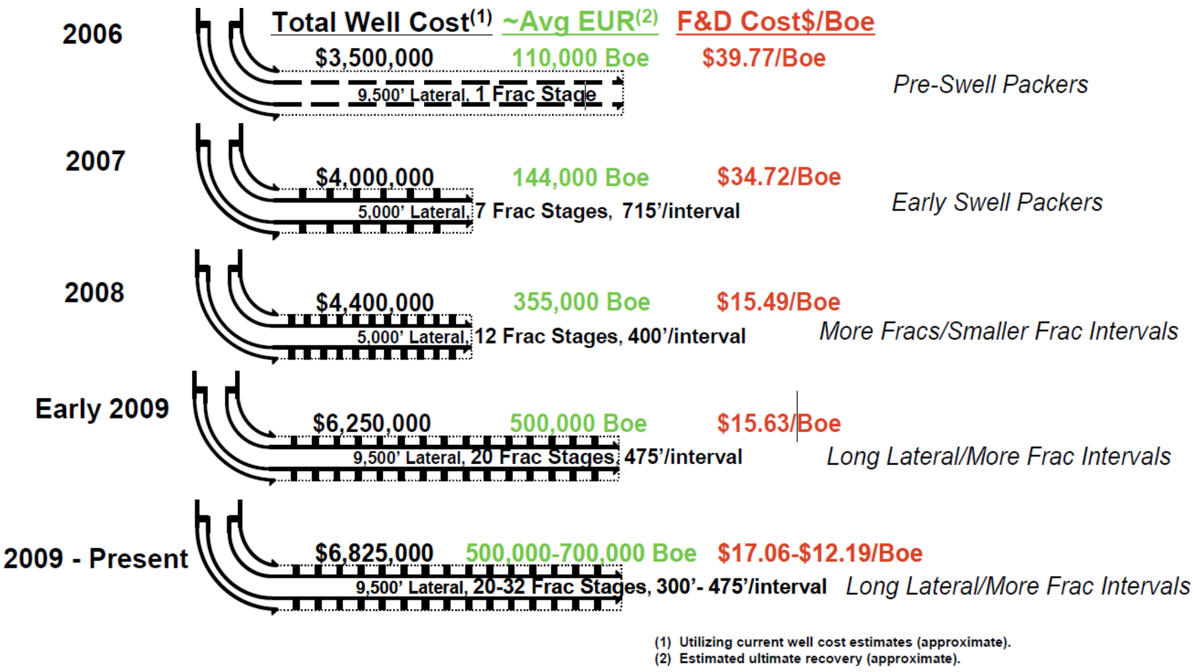


Figure 3. Improvements in shale well economics through adjustments in completions and drilling strategies (R. Rankin et al, 2010).

5.2 System Characteristics

The base EGS well flowrate of 125 l/sec or 68,000 BWPD was based upon Enhanced Geothermal Shot Analysis for the Geothermal Technologies Office (Augustine 2023) for the Technology Improvement (TI) scenario described in the GeoVision study (DOE 2019). This starting point relies upon the GETEM input parameters that can be used as input distributions based upon the perceived impact of recent and projected technology advances. The installed capacity relies heavily on the fractured volume, temperature, and flow rate of the system. The base case of this stochastic model uses an approximate power capacity per well of 5 MW which can be aggregated up to 100 MW for a single power plant using pad drilling to drive efficiencies of scale. This relates to a stimulated volume needed to support an EGS (Butler et al. 2007). There are many factors that influence this power capacity. Fractures may close over time and the temperature of the reservoir is diminished. However, there is also research that indicates the thermal contraction of rock may lead to fracture conductivity enhancement over time (Butler et al. 2007). The initial power capacity uncertainty impacts on project economics will be examined within the model.

The thermal decline, defined as the decrease in produced fluid temperature over time, can be optimized with effective injection fluid conformance. The best case with lowest thermal decline results from injection water distributed evenly in the induced fractures as shown in Augustine's (2016) analysis of induced fractures using Gringarten et al. (1975) model, shown in Figure 4 below. The heat maps show the effects of water pumped through fractures of varying spacing and aperture and the resultant cooling. The first heat map shows a perfect distribution of fluid in each fracture, on the graph to the right, which is the top curve with the slowest thermal decline of the system – that is perfect flow conformance. The dashed curves on the graph are alternative states of flow conformance seen in the heat maps to the left. The green arrow represents the uplift in heat production possible if one achieves optimal conformance control and the ability to stop the highly conductive fractures from short-circuiting from the injector to the producer – this is the economic benefit possible with flow control devices, similar to oil field waterfloods, and has a tremendous ROI for the additional cost of the conformance system.

In Augustine's (2016) analysis, the thermal decline difference between a uniform spacing and aperture scenario vs. a variable spacing and aperture scenario is notable. After 20 years, the uniform case experiences a decline of only 3°C. where the worst variable case experiences nearly 27°C of additional thermal decline in production temperatures or 900%. This is the economic benefit of conformance control, similar to oil field waterfloods, and has a tremendous ROI for the specific flow control system if the base thermal decline is significantly higher without it.

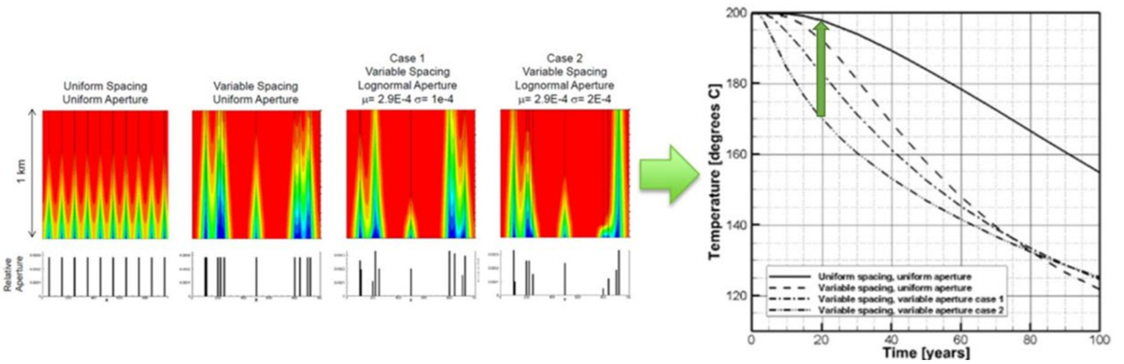


Figure 4: Figure 2 of Augustine's (2016) analysis of induced fractures using Gringarten et al. (1975)

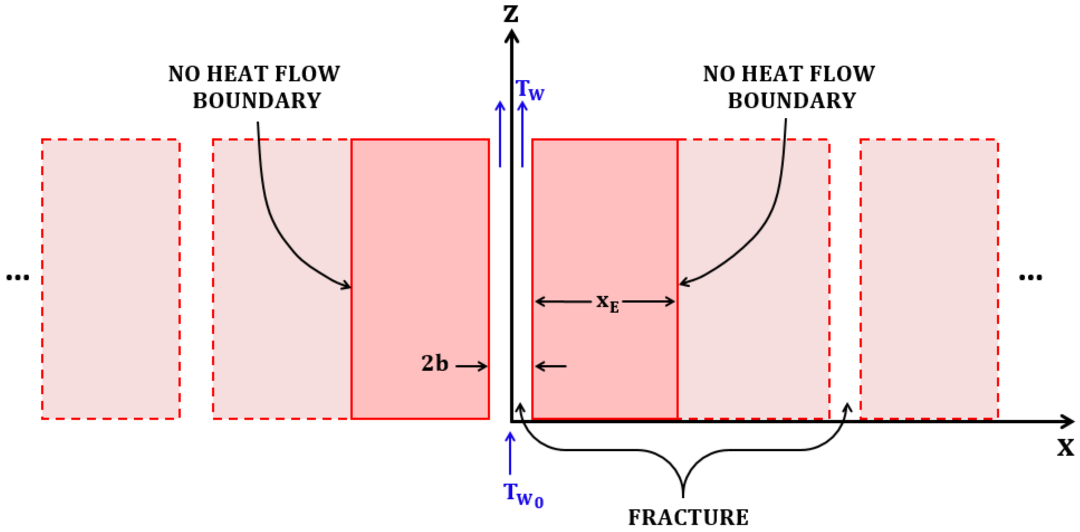


Figure 5: Gringarten et al. bilinear model for fractured hot dry rock. Nomenclature: 2b = fracture width, 2xe = fracture spacing, h = fracture height

5.3 Reservoir Modeling

A 3D numerical model has been developed which closely addresses the use of hydraulic fractures connecting either an injection-production well pair or one injection well and two producers to improve heat extraction and reduce well-system development cost.

The heat transfer equations in the x-y-z domain (x the horizontal coordinate parallel to the fracture face, y the horizontal coordinate perpendicular to fracture face, and z the vertical coordinate parallel to the fracture face) are given below.

Heat balance within each hydraulic fracture—advection-conduction heat flow without leak-off:

$$-\underbrace{\left(\rho_w c_w u_w \frac{\partial T_f}{\partial x}\right)}_{\text{Heat Advection in HF}} - \underbrace{\left[-\left(\frac{K_m}{w_f / 2}\right)\frac{\partial T_m}{\partial y}\bigg|_{y=w_f/2} - \left(\frac{K_m}{dz / 2}\right)\frac{\partial T_m}{\partial z}\bigg|_{z=dz/2}\right]}_{\substack{\text{Conduction of Heat at the}\\ \text{Fracture-Matrix Interface}}} = \underbrace{\rho_f c_f \frac{\partial T_f}{\partial t}}_{\substack{\text{Rate of Heat}\\ \text{Accumulation}\\ \text{in the Fracture}}} \tag{1}$$

Heat balance in the rock surrounding hydraulic fracture:

$$\underbrace{\frac{\partial}{\partial x} K_{R,x} \frac{\partial T_R}{\partial x} + \frac{\partial}{\partial y} K_{R,y} \frac{\partial T_R}{\partial y} + \frac{\partial}{\partial z} K_{R,z} \frac{\partial T_R}{\partial z}}_{\substack{\text{Heat conduction}\\ \text{in the rock matrix}\\ \text{surrounding fracture}}} = \underbrace{\rho_R c_R \frac{\partial T_R}{\partial t}}_{\substack{\text{Rate of heat}\\ \text{accumulation}\\ \text{in the rock matrix}}} \tag{2}$$

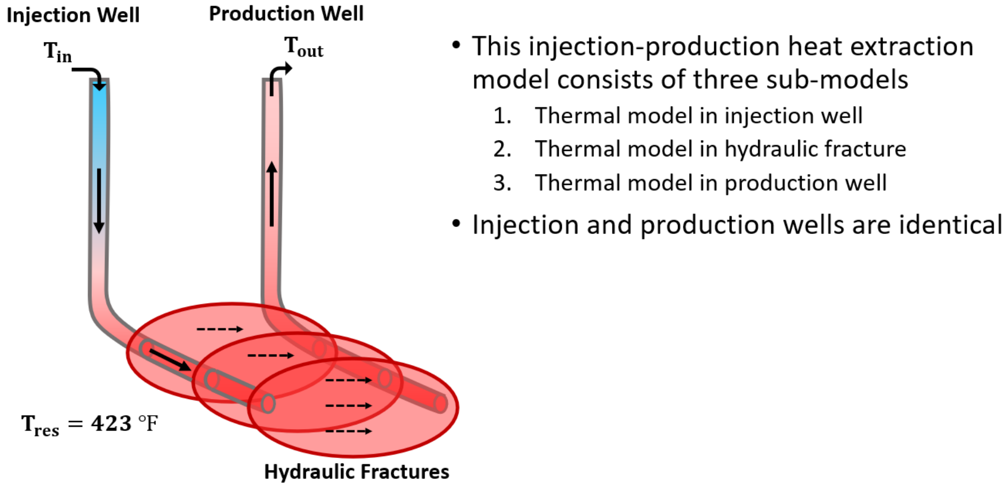
No heat flow in the rock between two hydraulic fractures:

$$\frac{\partial T_R}{\partial y}\bigg|_{y=\mathrm{L}_y/2} = 0 \tag{3}$$

Inlet velocity boundary condition:

$$u_{x,w,hf}\Big|_{x=0} = q_{inj} / \left(w_{hf} h\right) \tag{4}$$

The following figure is the current idealized configuration of injection-production wells connected by three hydraulic fracture stages in the Utah FORGE field research location. In the figure the injection-production wells appear to have been placed at the same depth; however, in the actual case the producing well is directly above the injection well.



- This injection-production heat extraction model consists of three sub-models
  1. Thermal model in injection well
  2. Thermal model in hydraulic fracture
  3. Thermal model in production well
- Injection and production wells are identical

Figure 6: 3D idealization of injection-production wells connected with three hydraulic fracture stages for heat extraction form the hot and dry Utah FORGE field research location.

5.4 Presented Stochastic Economic Model

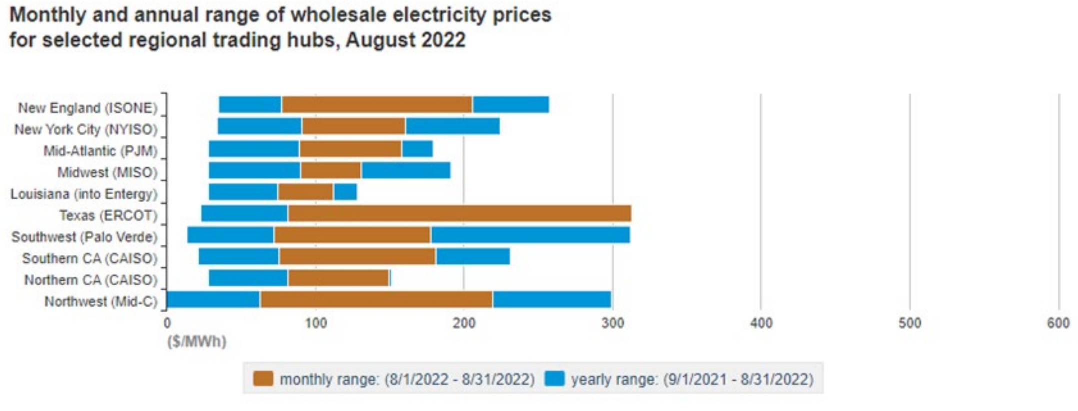
The presented model uses stochastic modeling @RISK software to evaluate the variables present in an EGS development in an efficient, concise manner. The common financial yardsticks of NPV and ROI can be used with Monte Carlo Simulation to understand the economic opportunities and risks associated with such an investment. A 30-year cashflow model was constructed using Excel, and the stochastic add-in @Risk examined the EGS economics of the specific design considerations and opportunities for economies of scale to reduce costs in a hot dry rock EGS, using the conditions at the Utah FORGE project as a model. Two cashflow models were constructed; a “Base” case of an EGS system constructed with three wells using cased and cemented laterals approximately 10,000’ using multi-stage fracturing in each well using Plug and Perf completion methods.

A second cashflow model, “Change”, was created that was nearly identical to the first, but was adjusted to reflect changes to the EGS well construction and operating practices consistent with the installation of an EGS system capable of conformance control to improve thermal decline, such as the dual purpose frac sleeve developed as part of the DOE Funded Utah FORGE project, called the GeoThermOPTIMAL system. This system, described in (Fleckenstein 2022), allows both the multi-stage fracturing necessary to create the EGS system, and later during the productive life of the system, uses a high temperature wireline tractor, for conformance control of the EGS system and the prevention of a “short circuit” between the injector and the producer. The second cashflow model allows additional factors’ variability to be included and analyzed for economic impact, such as higher drilling rates, inclusions of open hole vs. cased hole completions, power pricing, carbon pricing, flow rates, thermal decline rates, etc.

The difference between the two cashflow models is the economic value of change in operating condition, like the use of conformance control, such as the GeoThermOPTIMAL system, but also can be used for the evaluation of other capital expenditures and operating practices such as the use of a hybrid binary power plant to use natural gas to continue to operate a power plant at a constant temperature regardless of thermal decline of the system. Key components of the model include the typical variables in an EGS economic model including drilling and completion costs, system flow rate, thermal decline rate, cost of conformance control system such as GeoThermOPTIMAL, initial plant development costs and additional capex, such as power lines, roads etc., initial operating cost with cost inflation rate, and energy prices with price inflation rates as well as carbon pricing and discount rates.

High rates of fluid injection into single fractures cools the produced water quickly since the heat transfer can't keep up – "short-circuiting". Fractures should be spaced in a manner to ensure that fluid velocity from the injector to the producer does not exceed the thermal transfer capacity of the rock. Well spacing will depend on the fracture morphology which is defined as the number of fractures propagated in the far-field divided by the number of fractures initiated at the wellbore. The fracture morphology is a key metric for the spacing of coupled horizontal wells and is described in Cipolla, 2022. A variety of methodologies are used to quantify fracture morphology, such as sealed wellbore monitoring techniques as described in Haustveit, 2020.

Wholesale power prices for different regions in the United States vary greatly in all locations of the year. As shown in Figure 7, the cost of energy varies greatly depending on the time of year. This is the result of greater energy demand variability during summer and winter weather extremes. This highlights one of the benefits of geothermal energy; the base load deliverability remains fairly consistent regardless of wind and solar conditions, providing needed power deliverability. EGS is particularly attractive in California due to increasing Renewable Power Standards and the worsening of the mismatch of power demand and solar and wind deliverability. Consequently, California has the most installed geothermal capacity. In 2021, 5.7% of California's in-state power generation came from geothermal energy at 11,116 GWh (California Energy Commission, 2021).



eia Source: U.S Energy Information Administration based on SNL Energy

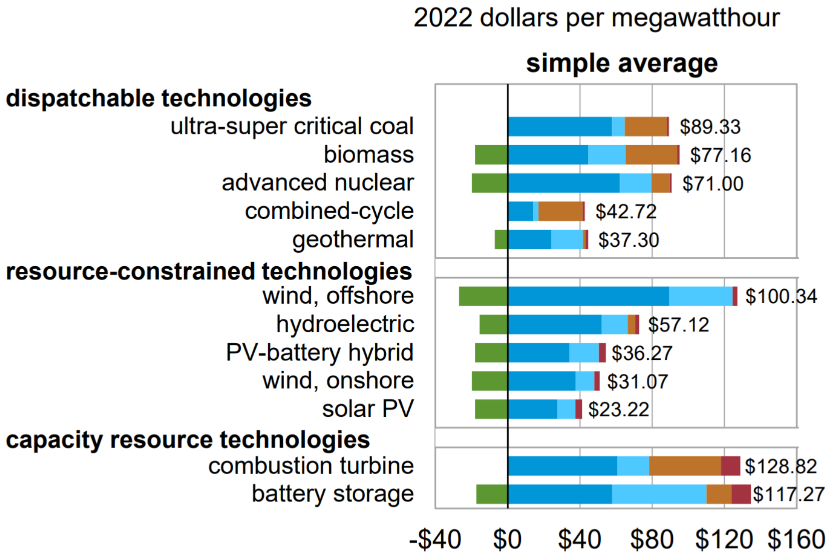
Figure 7: Regional Range of Wholesale Energy Prices in the United States (EIA, 2022)

Electricity generated from wind and solar energy is typically sold under power purchase agreements (PPA), which are long-term (about 20 year) contracts with prices that are either fixed or indexed to the power purchaser's "avoided" power costs (i.e., the cost the purchaser would have incurred itself had it produced the electricity it is purchasing from third parties). Wind and solar power producers sign these long-term PPAs with corporate clients (which want to reduce their carbon footprint) or with integrated utilities that deliver the renewable electricity to their customers. Similarly, electricity from geothermal power plants is currently mostly sold under these PPAs, which reduce the price volatility and increase the revenue visibility for the geothermal power producer. However, future geothermal projects may opt to sell the produced electricity without long-term PPAs as "merchant facilities" into the electricity spot or forward market, which increases the project's market volatility.

For this model, we assume that the produced electricity is sold under long-term PPAs at an average PPA price of $95 per MWh used as the starting point. This average PPA power price also appears reasonable when compared to the range of wholesale electricity prices in the USA in Figure 7. The power price uncertainty is driven by the success or failure of a variety of energy initiatives and can be quantified by stochastic distributions. Both the cost per MWh and its inflation rate can be adjusted from the base case in the model using an input distribution.

Our stochastic model also calculates the distribution of the levelized cost of electricity (LCOE) for our "base case" and "change case" cash flow models. The LCOE represents the estimated costs to build and operate our EGS plant and to generate the total electricity over the lifetime of the geothermal power plant (which is 30 years for our cash flow model). It is calculated as the NPV of the total costs (capex plus OPEX) relative to the NPV of total electricity produced in MWh (megawatt hours) and expressed in USD/MWh.

The LCOE can also be calculated for other technologies and is useful for comparing the production costs of generation power from different technologies to determine their relative cost competitiveness. The EIA provides an overview in the Annual Energy Outlook 2023 for the most current LCOE Projections for 2028 in the figure below for different power generation technologies in 2022 dollars. Given technological advancements, the 2028 LCOE has significantly declined for all technologies over the recent years, but in particular for onshore wind and solar PV, but also including geothermal. This requires significant technology driven reductions in costs, which is reflected in the lower boundaries of stochastic models in the @Risk cost distributions.



Data source: U.S. Energy Information Administration, Annual Energy Outlook 2023

Figure 8: Annual Energy Outlook 2023 for the most current LCOE Projections for 2028 (EIA, 2023)

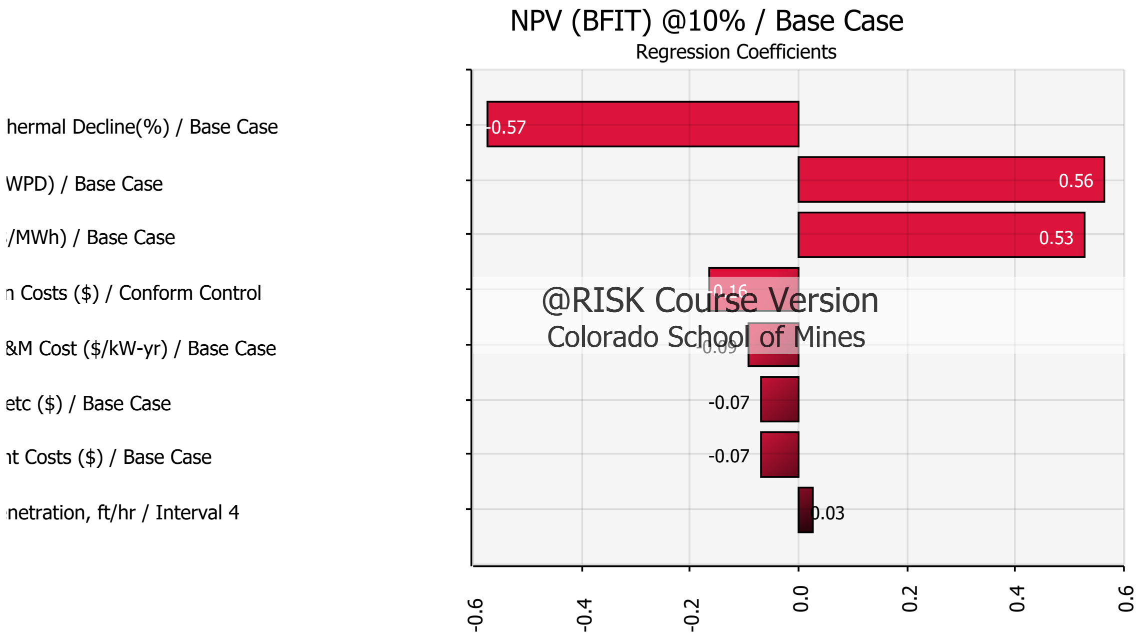
6. EGS Stochastic and Deterministic Economic Modeling Results

Multiple stochastic simulation runs were made using the cashflow model with representative deterministic and stochastic model variables and results in Tables 1 & 2. The base case was made with a three well EGS system, with three long horizontals, cased, and cemented wells using "Plug and Perf" multi-stage stimulation. One of the horizontal wells is an injector and two are producers, taking advantage of the bi-wing induced fractures. The second case also has two producers, but these are openhole producers, with stimulation only being done on the injection well, which is also equipped with conformance sleeves.

Investment Parameters	Base Case	Conformance Control With Openhole Comp.
Drilling Costs ($) 1 injector, 2 producers	12,231,817	9,570,394
Completion Costs ($)	15,000,000	5,000,000
Initial Plant Development Costs ($)	12,000,000	12,000,000
Addition Capex -Power Lines, Roads, etc. ($)	12,000,000	12,000,000
Conformance Control Capex ($)		3,000,000.00
Total Initial Investment ($)	51,231,817	41,570,394
Flow Rate (BWPD) (125 l/sec equals 68,000 BWPD)	68000	68000
Annual Thermal Decline (%)	3.0%	2.0%
Annual O&M Cost ($/kW-yr)	175	175
Initial Monthly Operating Cost ($)	93,417.48	93,417.48
Monthly Operating Cost Inflation Rate (%)	5%	5%
Hypothetical 10-Year Workover Cost ($)	1,000,000	1,000,000
Hypothetical 20-Year Workover Cost ($)	2,000,000	2,000,000
Initial Wholesale Energy or PPA Price ($/MWh)	95.00	95.00
Wholesale Energy Price Inflation Rate (%)	4%	4%
Discount Rate (%)	7%	7%
Levelized cost of energy ($/MWh)	144	132
NPV (BFIT) @10%	23,514,643	37,374,965
ROI (BFIT) @10%	0.46	0.90

Table 1. Representative deterministic model variables and results

The stochastic model variables in Table 2 for example used triangular distributions for thermal declines with a most likely value of 3% but varied from 1% to 5%, as shown in Figure 10 below with other variables using similar distributions. The sensitivity analysis presented in Figure 9 for the base case reveals the three most important factors for a higher EGS NPV: the system thermal decline, the flowrate of the system, and the power prices. The conformance control value improved with the greater thermal decline of the system, and from the Figure 9 results one can conclude that the larger thermal decline of the base system the more important the conformance control. Conversely, if there is little thermal decline in the system, conformance control has little value. However, the LCOE is high in both cases due to the high capital requirements required for drilling and completing of the wells, power plants, and associated expenditures. The sensitivity analysis of the system economics indicates that if economies of scale are possible that are similar to shale development, with longer laterals approaching 20,000’, and the shale well manufacturing processes can be adopted to EGS, a step decrease in LCOE is possible.



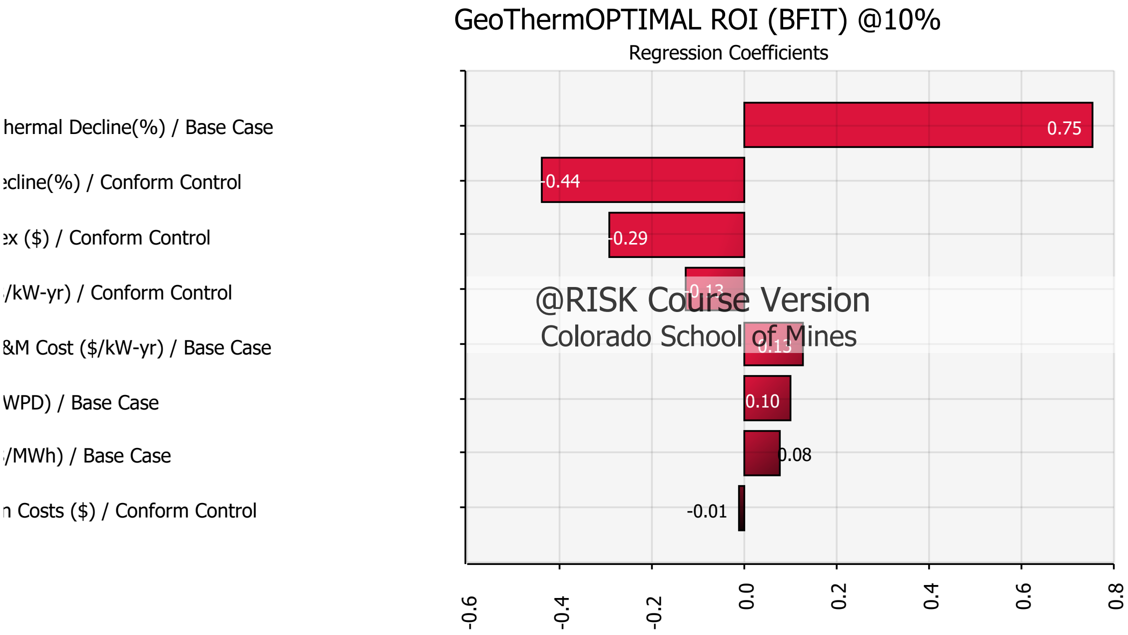


Figure 9: Sensitivity analysis of NPV of EGS System and of the ROI of conformance control example using the GeoThermOPTIMAL system being developed as part of the Utah-FORGE Project

If one considers the distributions below for the three factors with the largest impact on the NPV in the base case project the system values needed for the most improvement can be predicted and designed to achieve optimal economics. These distributions are randomly sampled around the most likely value, with a bias towards the best estimate, but the ranges of the distribution accounting for the impact of higher and lower values in the thermal decline has the largest impact on both the NPV of the EGS project described in the table above, and also the value of the conformance control system to reduce the thermal decline. The thermal decline of the conformance control system only reduces the thermal decline from a most likely value of 3% annually in the base case to 2% in the conformance control case, with much higher NPV and ROI the larger the base case thermal decline. In other words, the lower the base case thermal decline, the lower the value of remediating it. In oilfield waterflooding experience, the least expensive solution to conformance control is the use of pre-installed mechanical systems that can be activated with non-rig workovers.

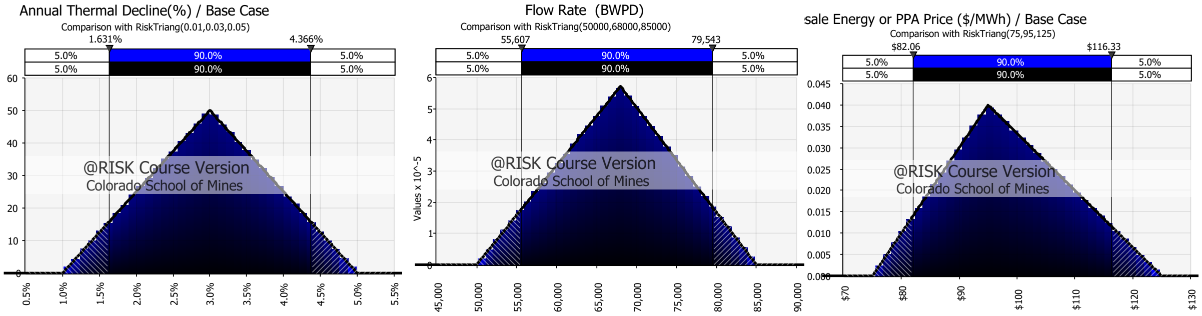


Figure 10: Representative triangular distributions for Thermal Decline, Flow Rate and Power Pricing

The value of the conformance control is captured in the probability distribution of the difference is NPV generated by the base case and conformance control with a small improvement in thermal decline with a 90% confidence factor of a positive NPV outcome. The large upside gives incentive to attempt new technologies and well construction practices, like open hole completions in producers to receive connecting fractures initiated from the injection wells. The individual well risks are covered by the uplift in value from the improved conformance control for the entire EGS.

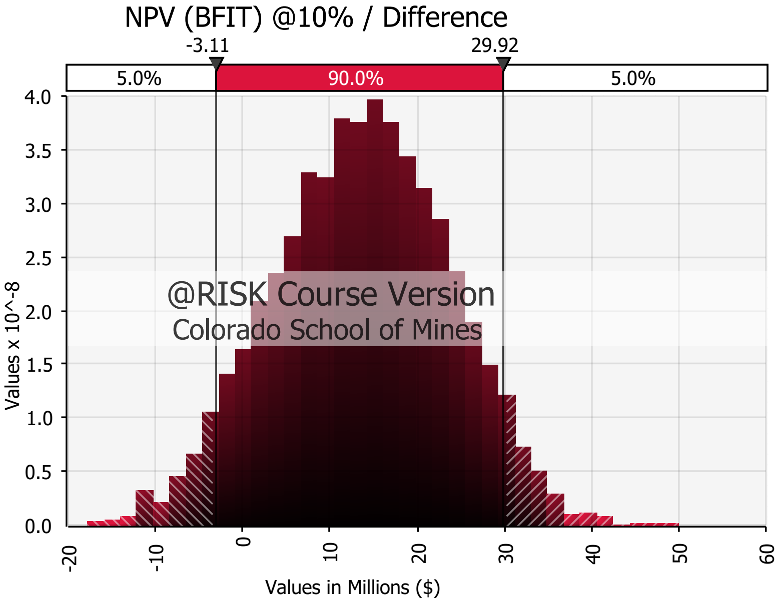


Figure 11: Probability distribution of the NPV of conformance control and openhole producers

The wide range in the probability distribution of Figure 11 and the high impact of the thermal decline uncertainty on the project NPV provides a roadblock to project investment. The combination of natural gas with geothermal produced water provides a mechanism to limit the thermal decline, and provides an uplift in the project economics with the use of lower cost natural gas as a thermal source. The natural gas provides insurance against premature thermal decline of the system, while the overperformance of the EGS system provides upside by minimizing the cost of natural gas, moving the system NPV to the higher side of the probability distribution curve. The value of carbon avoidance will motivate operators to improve the performance of the EGS to minimize and eventually eliminate the use of natural gas as a contributing factor to higher operating costs. Other technological improvements may be used to limit thermal decline, including thermal solar and energy storage using injection water heated by excess electricity during imbalances between peak demand and solar power generation as described by the “Duck Curve”.

Economics were relatively insensitive to drilling rate increases, but step rate improvements in well construction such as openhole completions, monobores, or other unforeseen technology improvements such as composite and later dissolvable bridge plugs, top drives and friction reducing technologies in shale development, are predictive of reduced costs and improved LCOE for EGS. In the following table, these economies of scale are investigated, with the sensitivity analysis for the NPV of EGS under a technology advance and economies of scale scenario presented in Figure 12. The importance of high flowrates, resulting from improvements in lateral lengths and low thermal declines are also key economic drivers. Cuts in operating costs and lower capital costs are key to reducing the EGS LCOE to the levels envisioned by the The Enhanced Geothermal Shot™.

Investment Parameters	Base Case	Technology Advance Economies of Scale
Drilling Costs ($) 1 injector, 2 producers	12,231,817	9,570,394
Completion Costs ($)	15,000,000	5,000,000
Initial Plant Development Costs ($)	12,000,000	6,000,000
Additional Capex -Power Lines, Roads etc. ($)	12,000,000	6,000,000
Conformance Control Capex ($)		3,000,000
Total Initial Investment ($)	51,231,817	29,570,394
Flow Rate (BWPD) (125 l/sec equals 68,000 BWPD)	68,000	140,000
Annual Thermal Decline (%)	3.0%	2.0%
Annual O&M Cost ($/kW-yr)	175	100
Initial Monthly Operating Cost ($)	93,417	109,902
Monthly Operating Cost Inflation Rate (%)	5%	5%
Hypothetical 10-Year Workover Cost (%)	1,000,000	1,000,000
Hypothetical 20-Year Workover Cost (%)	2,000,000	2,000,000
Initial Wholesale Energy or PPA Price ($/MWh)	95.00	95.00
Wholesale Energy Price Inflation Rate (%)	4%	4%
Discount Rate (%)	7%	7%
Levelized cost of energy ($/MWh)	144	68
NPV (BFIT) @10%	23,514,643	150,479,875
ROI (BFIT) @10%	0.46	5.09

Table 2. Representative stochastic model variables and results

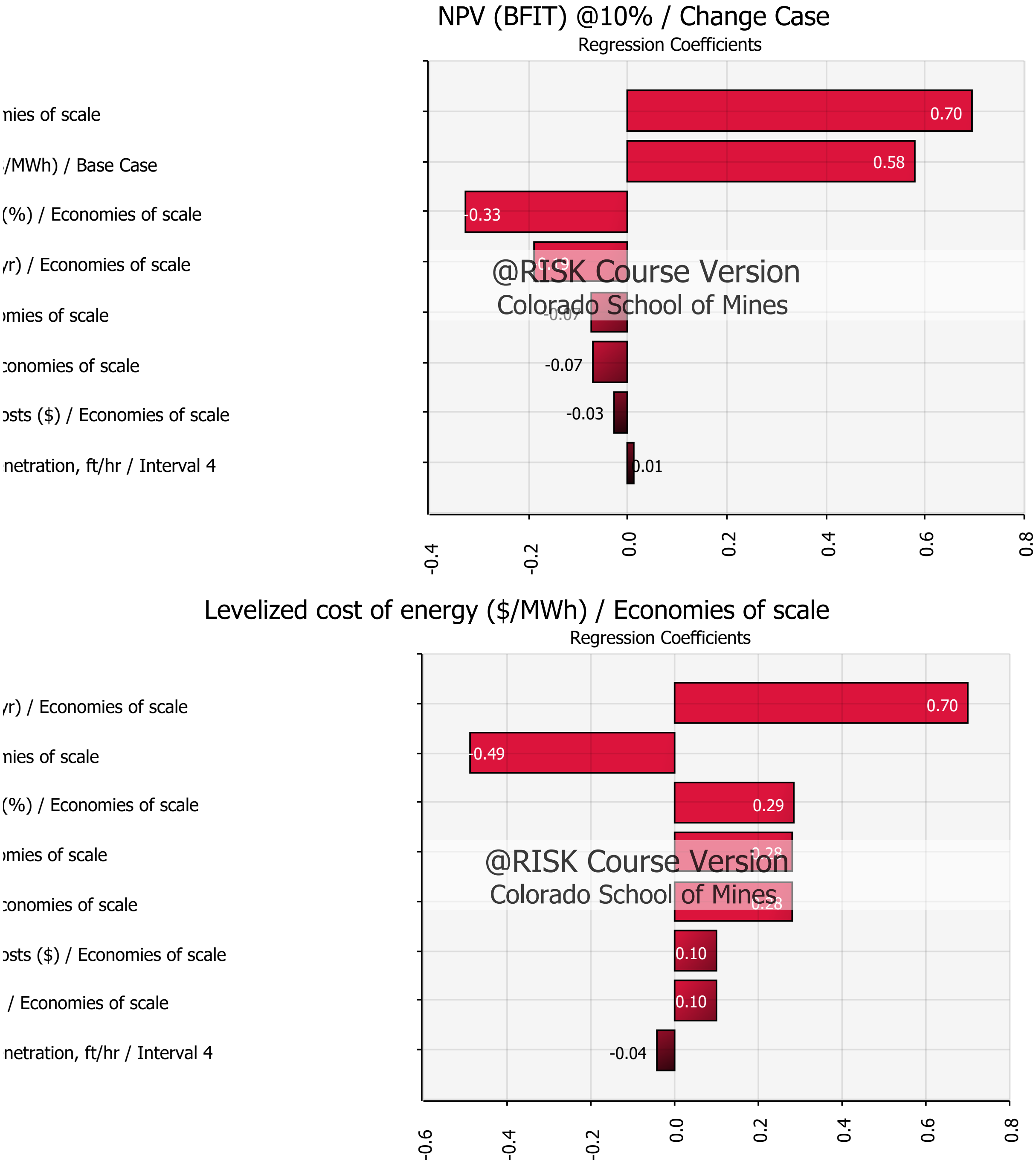


Figure 12: Sensitivity analysis of NPV and LCOE of EGS system with Economy of Scale improvements

7. Conclusions

1. EGS systems require significant economies of scale to become investible and scalable as a function of system flowrate, power pricing, and thermal decline rate; however, thermal decline has the biggest economic value impact if significant. The levelized cost of energy (LCOE) was impacted by the operation and maintenance (O&M) costs as well as thermal decline, power plant and associated capital investment requirements.

2. Regardless of other factors, the low thermal decline is necessary for economically viable enhanced geothermal systems (EGS). Furthermore, conformance control systems are needed to address potential subsurface heat loss resulting from flow channeling of the circulating fluid when it occurs.

3. Natural gas use for makeup heat generation should provide a solution to unexpected EGS thermal decline to overcome capital investment hesitancy until economies of scale of the innovations, similar to the early days of the "shale revolution, reach a self-sustaining level. The probable natural gas usage for heat generation makeup will have a small imprint on the carbon emission levels because it can be sequestered in the vicinity of the thermal project.

Nomenclature

ρ_w = Density, lbm/ft^3

c_f = Heat capacity of water in fracture, Btu/lbm.°F

c_R = Heat capacity of matrix rock, Btu/lbm.°F

h = Fracture height, ft

q_w = Water injection rate, ft^3/hr

t = Time, hour

$K_m = K_R$ = Heat conduction coefficient in matrix rock, Btu/ft.hr.°F

T_f = Fracture temperature, °F

T_m = Matrix temperature, °F

u_w = Water velocity in fracture, ft/hr

x, y, z = Cartesian coordinates, ft

w_f = Hydraulic fracture width, ft

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