Cost Optimization for Geothermal Well Drilling
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1. Introduction

As fossil fuels become a limited resource, the world will be forced to develop alternative sources of energy. One of these possible sources is geothermal energy. Under ideal circumstances, geothermal systems should be a low hanging fruit on the tree of renewable energy. It is flexible, reliable, environmentally friendly, and available throughout the world. The United States has enough geothermal power available to be entirely energy independent for 30,000 years\(^1\). However, in our less than ideal world, geothermal energy turns out to be anything but practical, mainly due to its immense capital costs.

Nevertheless, there is hope for geothermal energy. Current models indicate that with improved energy extraction methods, the cost of geothermal electricity can be brought down to very competitive levels. In addition to technological advancements, various parameters of a geothermal system can be optimized to minimize cost. Currently, the largest variable in determining the cost of geothermal power is the well used to extract the steam and water. If well costs can be minimized, it is likely that the amortized cost of geothermal energy can be minimized as well. I will explore a method of minimizing the cost of geothermal well drilling by considering the variation of energy content and well cost with depth.

2. The Current Standing of Geothermal Energy

Before the specifics of geothermal energy are discussed, it is helpful to understand just how these power plants work. We will be focusing on what is known as an Enhanced Geothermal System (EGS). An EGS works as follows: cool water is pumped deep into the Earth using a series of injection wells. The wells are drilled so that the rock near the bottom of the well has a temperature of at least 200 °C. The water then travels through fractures in the rock to a nearby production well, where the heated water is pumped to the surface and used to generate electricity. Once the water has cooled to the point where it can no longer be used to generate electricity, the water is again pumped down the injection well and the process starts over. Figure 2.1 shows a schematic of a basic geothermal power system:

Even though this energy source appears to be relatively easy to implement, geothermal power plants are rarely used on a large scale. The main reason for this is the large cost of developing the EGS infrastructure. According to *The Future of Geothermal Energy*[^3], the infrastructure can be broken up into three groups:

1. Exploration and drilling of test and production wells
2. Construction of power conversion facilities
3. Discounted future redrillings and well stimulation.”

Of these, the costs for drilling and maintaining the initial wells accounts for roughly 50% of the total capital cost of a plant[^3]. Therefore, even though EGS does not require continuous expenditures on fuel to produce electric power, the operational and maintenance costs are still very large. Unfortunately, this has restricted the production of geothermal energy in the energy marketplace. Due to these large costs, only small amounts of geothermal electricity are produced in the United States. Figure 2.2 helps illustrate the current and projected standing of geothermal energy against other renewable electricity sources.

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As can be seen, geothermal energy makes up a small percentage of the total renewable electricity production. Given that renewables are a very small portion of the total electricity production in the United States, the amount of geothermal electricity is even smaller than one might think. The Energy Information Agency estimates that less than 1% of electricity produced in the United States comes from geothermal power plants, even though North America has the largest reserves for geothermal energy in the world. Projections forecast that the supply will continue to remain low.

Nevertheless, the technology for EGS is forecasted to further improve, which would lower electricity prices to competitive levels. If the energy extraction methods are further improved, it is possible that geothermal plants could produce electricity for as low as 0.04 $/kWh. So, even though this type of energy may not be economically viable at the present, it could become viable in the future. However, the issue of drilling costs remains, and is not likely to improve substantially. No matter what technological improvement occurs to facilitate better energy extraction, maximize turbine efficiency, etc, it will still be expensive to drill the injection and production wells.

It is in the area of well drilling that an interesting problem arises. Every geothermal well has an operational lifetime when the rock temperatures are sufficiently high to generate sufficient amounts of steam. The deeper the well is drilled, the more energy is available and the longer the well is able to operate. Drilling deeper wells reduces the need to re-drill or re-stimulate wells that have cooled to the point where they are no longer feasible energy sources. However, as the well depth increases, so does the cost of drilling that well. These two facts suggest that there is an optimal depth for a geothermal well, a depth that minimizes the total cost of well drilling to keep

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a plant operational. To analyze this problem, it is necessary to construct a theoretical model that examines the cost per kilowatt-hour of electricity for various well depths.

3. Assumptions and Method

In order to reduce this problem to a manageable size, it was necessary to make several assumptions about the power plant and the geology of the Earth. The first deals with the power plant’s energy extraction method. It will be assumed that the water from the injection well flows through a uniform cylinder of rock toward the production well. In the process, the water lowers the temperature of the entire rock cylinder by an equal amount. This heat energy of the rock is transferred to the water and pumped out of the ground via a production well. Once the rock cylinder’s temperature has cooled to a predetermined abandonment temperature \( T_a \), usage of the well will be terminated, and a new well will be drilled.

For the geology of our plant site, we will assume that there exist only two rock types that the injection and production wells penetrate: a sedimentary or volcanic layer and a basement layer. Both layers contribute to the temperature at a specific depth \( X \). This temperature can be calculated using various characteristics of the two layers as shown in Figure 3.1. The values for most of the variables in these equations were given in the paper cited; in the interest of space they will not be repeated in this paper.

Figure 3.1\(^6\):

![Figure 3.1](Image)

Even though two rock types will be considered when calculating temperature, the heat capacity of the rock \( (C_p) \) will be assumed to be constant throughout the Earth, regardless of what rock type is present or what depth is being examined. To calculate the amount of energy that is

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physically available to be extracted from the rock \( (Q) \), we will use Equation 1. For a definition of symbols, see Appendix A.

\[
Q = F_r \rho V C_p (T_i - T_a) \quad (1)
\]

Of the total recoverable energy, only a small fraction will be converted into electricity due to the inefficiencies in the energy extraction methods and the inefficiency for the electricity generation. The efficiencies of energy extraction \( (\eta_e) \) will be assumed to be constant under all circumstances. The efficiency of the generators \( (\eta_g) \) will be assumed to depend on the temperature of the water pumped out of the production well. If we assume the water reaches the ambient temperature of the rock \( (T) \) at a given depth and point in time, the efficiency of the generators is given by the following function\(^7\):

\[
\eta_g = 0.0005T + 0.032 \quad (2)
\]

Considering the efficiency for the electricity generators, the amount of electricity produced by a well is given by Equation 3:

\[
Q_e = \eta_g \eta_e Q \quad (3)
\]

We now know how to calculate the electric energy that will be extracted from a well. The next major step is figuring out the cost of drilling a well at a specific depth. The cost of drilling the wells will be assumed to remain constant with time. The model for determining drilling cost (in 2005 dollars) based on current depth will be based on data compiled by the Idaho National Laboratory. For the purposes of this paper, we will use Equation 4, based upon EGS well costs compiled for the whole United States\(^8\): 

\[
C(X) = 107441e^{0.00024729X} \quad (4)
\]

Next, we need to determine how long a well will be operational. To determine the lifetime of a well, we will assume that the rate of energy extraction is proportional to the amount of energy present, i.e.:

\[
\frac{dE}{dt} = -kE \quad (5)
\]

In this case, \( k \) is the energy extraction rate. In this analysis, the value of \( k \) was chosen to match another EGS model’s thermal drawdown rate. The value of \( k \) was chosen to be \( k = 0.003 \), representing a thermal drawdown rate of 0.3% per year\(^9\). Solving this differential equation for \( E(0) = E_0 \), we get the following expression for energy at a time \( t \):

\[
E = E_0 e^{-kt} \quad (6)
\]

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From $E(t)$, we can calculate the current temperature of a reservoir, and determine the time at which the reservoir reaches the abandonment temperature. Using the cost and lifetime information presented so far, the total well drilling cost for the plant lifetime, $C_r(X)$, can be calculated using Equation 7.

$$C_r(X) = \frac{2\pi C(X)}{t_{well}} \quad (7)$$

Now that we have a way to calculate the total electric energy produced by a well, the well lifetime, and total cost for sustaining the wells for the desired lifetime of a plant, we can find the amortized cost per kilowatt hour of electricity produced by the plant. In this analysis, we will be using an amortization method provided by Microsoft Excel. The cost per kWh is given by Equation 8.

$$C(X)_{kWh} = Amt[C_r(X) + C_{plant}, r, E] \quad (8)$$

(Amt is the amortization function. See Appendix B for this function’s code).

Finally, we have the framework necessary to conduct an analysis of a range of geothermal wells. To analyze a range of depths, a computer program was written in Microsoft Excel to calculate the various parameters discussed so far. The program was designed to allow the user to specify all data entries in a user interface, and then perform the calculations over a range of well depths. The cost per kilowatt-hour of electricity was plotted against well depth to illustrate the results.

4. **Results of Analysis**

If we run the program on the data values given in Appendix A, we get the graph of cost per kWh vs. depth as shown in Figure 4.1. The initial conditions model a theoretical well in Nevada, a state popular with geothermal exploration. Most of the data is constant throughout large portions of the western United States (such as most of the constants involved in temperature calculation). The data specific to this well are the basement rock type (assumed to be generic granite), the ground temperature, the mantle heat flow, and the efficiencies involved in energy extraction and electricity generation.
The graph largely matches with intuition on cost at different depths. The asymptote at the left shows that depths that result in a well temperature close to the predefined abandonment temperature are highly unfavorable, as the wells have a short operational lifespan. For example, according to this simulation, a well of depth 5150 meters (initial temperature $T_i = 200.64 \, ^\circ\text{C}$) would require 22 re-drilled wells to serve a 25 year plant lifetime. These multiple re-drilling operations result in extremely expensive electricity costs.

If the well is drilled deep enough past this “abandonment threshold,” the number of required wells reduces to a manageable level. If the well is drilled too deep, the cost of the individual wells becomes the dominant factor in determining the cost per kilowatt hour. This is because the lifetime of an individual well can exceed the lifetime of the plant. Because the well cost rises exponentially with depth, it follows that the cost per kilowatt-hour also increases exponentially with depth when the well is sufficiently deep.

As can be seen from the graph, it appears an optimal depth for EGS well drilling does exist. For this example, the optimal depth was found to be approximately 6650 meters. Obviously, the optimal depth will be different for every well considered by the model. To find the optimal depth for a different well, the data specific to the new site in question needs to be supplied to the model using the program’s user interface.

Even though we appear to have found a nice solution to the problem of well depth optimization, there are several issues that need to be considered. One of these is the data used in the simulation, and the other relates to the assumptions used in the model. Both of these factors can greatly impact the accuracy of the conclusions drawn so far. Unfortunately, there is not much to be done about the simplifications made in creating the model. The complexities in implementing the watered down version were difficult enough, so the addition of more realistic features is beyond the scope of this project.
On the other hand, the potentially unrealistic data can be somewhat accounted for. Given that the data used in the first simulation may not be accurate, it would be beneficial to test the model over a wide range of initial conditions. If the results are generally the same throughout these tests, we can conclude with reasonable certainty that the correct data conditions, whatever they may be, will produce similar results. The graph of four sets of initial conditions is presented in Figure 4.2.

Figure 4.2:

As is evident, even though the optimal depths and costs for each set of initial conditions are different, the wells that are drilled just past the abandonment threshold are more economically feasible than the deeper wells. In fact, due to the low values of the derivative of the cost curve, as long as the depth of a well is within a small distance of the optimal depth, a reasonably cost effective well will be produced. Therefore, we can conclude that it is best to drill shallow wells, as long as the abandonment threshold is passed.

There is one final issue that needs to be addresses when considering these results. The minimum predicted cost of electricity is reported to be 1.43 $/kWh from the first trial run. This cost is quite high when compared to other, more sophisticated simulations of geothermal electricity costs. According to the MIT EGS model, the mean predicted cost for EGS electricity is 0.359 $/kWh\textsuperscript{10}. Even though my model is ideal and greatly simplified, the cost of electricity is predicted to be suspiciously high. Granted, due to the simplifications made in constructing the model, systematic error in the results is to be expected. This goes to show that the results of this analysis must be taken with a grain of salt due to the nature of the model.

[2649 words]\textsuperscript{11}


\textsuperscript{11} Word count does not include appendices
Appendix A: Definition of Symbols

\( \rho \) – Density of the rock (for granite, \( \rho = 2.6 \ \text{g/cm}^3 \))\(^{12}\)

\( C_p \) – Heat capacity of the rock (for granite, \( C_p = 0.79 \ \text{J/g} \cdot \text{°C} \))\(^{12}\)

\( V \) – Volume of the geothermal reservoir (calculated; \( V = \pi R^2 h \))

\( F_r \) – Energy recovery factor (taken to be \( F_r = 0.4 \))\(^{13}\)

\( E \) – Energy currently contained in the reservoir (calculated)

\( E_0 \) – Initial reservoir energy (calculated)

\( Q \) – Total recoverable heat energy (calculated)

\( Q_e \) – Generated electric energy (calculated)

\( X \) – Well depth (variable)

\( T_i \) – Initial reservoir temperature (calculated)

\( T_a \) – Abandonment temperature (taken to be \( T_a = 200 \ \text{°C} \))

\( T(X) \) – Temperature at depth \( X \) (calculated)

\( k \) – Energy extraction constant (taken to be \( k = 0.003 \))

\( \eta_g \) – Generator efficiency (calculated)

\( \eta_e \) – Extraction efficiency (taken to be \( \eta_e = 0.9 \))

\( C(X) \) – Cost to drill a well to a given depth \( X \) (calculated)

\( C_t(X) \) – Total cost of drilling all necessary wells over a plant’s lifetime (calculated)

\( C_{\text{plant}} \) – Cost to construct a geothermal plant (taken to be \( C_p = $125,000,000 \))\(^{14}\)

\( C(X)_{\text{kWh}} \) – Electricity cost per kWh at a given depth \( X \) (calculated)

\( \tau \) – Predefined plant lifetime (taken to be \( \tau = 25 \) years)

\( t \) – An arbitrary point of time in a well’s operation

\( t_{\text{well}} \) – The lifetime of a well (calculated)


Appendix B: ‘Geothermal Analysis’ Source Code

Private Sub cmdCalculate_Click()
    'declares a lot of variables
    Dim spHeat As Double
    Dim length As Double
    Dim radius As Double
    Dim density As Double
    Dim gradient As Double
    Dim flowRate As Double
    Dim startDepth As Double
    Dim finalDepth As Double
    Dim stepSize As Double
    Dim volume As Double
    Dim mass As Double
    Dim currentDepth As Double
    Dim currentTemp As Double
    Dim timePerWell As Double
    Dim totalEnergy As Double
    Dim energy As Double
    Dim cost As Double
    Dim minTemp As Double
    Dim effTotal As Double
    Dim wellsNeeded As Double
    Dim mu As Double
    Dim energyElectric As Double
    Dim recovFactor As Double
    Dim efficiencyGenerator As Double
    Dim effExtract As Double
    Dim years As Double
    Dim costTest As String
    Dim minTempUsed As Double
    Dim cell As Integer

    ' should the efficiency of the generator remain constant,
    ' or should the efficiency be calculated?
    If (Sheet1.Range("K6") = "NA") Then
        efficiencyGenerator = -1
    Else
        efficiencyGenerator = CDbl(Sheet1.Range("K6"))
    End If

    ' some initial values of variables
    stepSize = CDbl(Sheet1.Range("J2"))
    spHeat = CDbl(Sheet1.Range("K7"))
density = CDbl(Sheet1.Range("K8"))
length = CDbl(Sheet1.Range("K9"))
radius = CDbl(Sheet1.Range("K10"))
startDepth = CDbl(Sheet1.Range("K11"))
finalDepth = CDbl(Sheet1.Range("K12"))
minTemp = CDbl(Sheet1.Range("K13"))
flowRate = CDbl(Sheet1.Range("K14"))
years = CDbl(Sheet1.Range("K15"))
effExtract = CDbl(Sheet1.Range("K16"))
costTest = CStr(Sheet1.Range("K17"))
recovFactor = 0.4 ' Future of GTE, pg. 3-10

' checking to make sure input is reasonable
If (efficiencyGen > 1) Or (effExtract > 1) Then
    MsgBox ("Efficiencies must be less than or equal to 1.0")
    Exit Sub
End If

' some calculations independent of the loop
density = density * 1000 'convert to kg/m^3
spHeat = spHeat * 2.778 * (10 ^ -4) 'convert units to kWh/kg*C
volume = 3.14159 * (radius ^ 2) * length
mass = density * volume

' some extra data that is useful
spHeatWater = 4.186 'joules / g * C
spHeatWater = spHeatWater * 2.778 * (10 ^ -4) 'convert to kWh/kg*C

' start the depth at a user defined point
currentDepth = startDepth
' the initial cell to record data to
cell = 2

' clears previous data
Call clearData

For x = startDepth To finalDepth Step stepSize

    'get the current temp and cost to drill the well
    currentTemp = temperature(currentDepth) 'C
    costOfWell = wellCost(currentDepth) * 1000 '$

    ' calculates the efficiency of the generator
    ' Future of Geothermal Energy, pg. INSERT
    If efficiencyGenerator = -1 Then
        effTotal = getEff(currentTemp) * effExtract
    Else
        effTotal = efficiencyGenerator * effExtract
    End If

End For
'get the energy of the reservoir in kWh
totalEnergy = spHeat * currentTemp * mass
finalEnergy = spHeat * minTemp * mass

'this is the amount of energy that can be used
'   by a power plant (in kWh)
energy = spHeat * mass * (currentTemp - minTemp) * recovFactor

'prevent division by zero (does not harm calculation's accuracy)
If energy = 0 Then
    energy = 1
End If

'get energy that becomes electric power (per well)
energyElectric = effTotal * energy

'get the total life of the well being considered
timePerWell = wellLife(totalEnergy, minTemp, mass, spHeat)

'make sure negative energy is taken care of
If Not (timePerWell = 0) Then
    wellsNeeded = years / timePerWell
    cost = 2 * wellsNeeded * costOfWell
    'total electricity produced
    energyElectric = energyElectric * wellsNeeded
Else
    wellsNeeded = -1
    cost = 0
End If

'cost per kWh or not (total cost otherwise)
If ((costTest = "YES") Or (costTest = "Yes")) Then
    cost = amortize(cost, years, energyElectric)
End If

'print the data to the spreadsheet
Sheet1.Cells(cell, 1) = currentDepth
Sheet1.Cells(cell, 2) = cost
Sheet1.Cells(cell, 3) = currentTemp
Sheet1.Cells(cell, 4) = energyElectric
Sheet1.Cells(cell, 5) = timePerWell
Sheet1.Cells(cell, 6) = RoundUp(wellsNeeded)

'increment the cells and depth
cell = cell + 1
currentDepth = currentDepth + stepSize
Next x

'set the axis scales for each of the charts
ActiveSheet.ChartObjects("Chart 1").Activate
ActiveChart.Axes(xlCategory).MinimumScale = startDepth - 100
ActiveChart.Axes(xlCategory).MaximumScale = finalDepth + 100

ActiveSheet.ChartObjects("Chart 11").Activate
ActiveChart.Axes(xlCategory).MinimumScale = startDepth - 100
ActiveChart.Axes(xlCategory).MaximumScale = finalDepth + 100

ActiveSheet.ChartObjects("Chart 12").Activate
ActiveChart.Axes(xlCategory).MinimumScale = startDepth - 100
ActiveChart.Axes(xlCategory).MaximumScale = finalDepth + 100
Range("A1").Select
End Sub

Function temperature(depth As Double) As Double
    ' calculates the temperature at a specific depth
    ' Uses the method in Future of Geothermal Energy, pg.
    Dim Q_0, Q_m, T_f, r, X_b, X_s, K_s, K_b, A_s, A_b As Double
    Dim part1_s, part2_s, part1_b, part2_b As Double
    Dim T_ground As Double
    Dim sedDepth, baseDepth As Double

    ' gets the values from the spreadsheet
    Q_0 = CDbl(Sheet1.Range("T4"))
    Q_m = CDbl(Sheet1.Range("T5"))
    r = CDbl(Sheet1.Range("T7")) 'meters
    sedDepth = CDbl(Sheet1.Range("T8")) 'meters
    baseDepth = CDbl(Sheet1.Range("T9")) 'meters
    K_s = 2.6 'W/m/K
    K_b = K_s 'W/m/K
    T_ground = CDbl(Sheet1.Range("T10")) 'C

    A_s = 10 ^ (-6) 'watt/meter^3
    A_b = (Q_0 - Q_m) / r

    If depth <= sedDepth Then
        X_s = depth
        X_b = 0
    Else
        X_s = sedDepth
        X_b = depth - sedDepth
    End If

    ' calculates the temperature due to the sediments
    part1_s = (Q_0 * X_s) / K_s
    part2_s = A_s * (X_s ^ 2) / K_s
    T_s = part1_s - part2_s

    ' calculates the temperature addition due to the basement
    part1_b = Q_m * X_b / K_b
    part2_b = A_b * (r ^ 2) * ((1 - Exp(-(X_b / r))) / K_b)
    T_b = part1_b + part2_b

    temperature = T_s + T_b
End Function
' return the final temperature
temperature = T_ground + T_s + T_b
End Function

Function wellCost(depth As Double) As Double
' computes the cost of drilling a well based on depth
' convert depth to feet
Dim x As Double
' convert the depth from meters to feet
x = depth * 3.2
wellCost = 1.07441 * 100 * Exp((2.40729 * (10 ^ -4)) * x)
End Function

Function RoundUp(x As Double) As Integer
' rounds a number x up to the next integer
If x = Round(x, 0) Then
    RoundUp = x
Else
    RoundUp = Round(x + 0.5, 0)
End If
End Function

Function amortize(cost As Double, projectLife As Double, _
energy As Double) As Double
'amortizes the cost of the electricity out over the project life
' provided by Prof. Evans' 'Amortization Workbook'
Dim intR As Double ' interest rate
Dim numPay As Double ' number of payments per year
Dim moPay As Double
Dim annPay As Double
Dim plantCost As Double
Dim PLC As Double ' peak load capacity (kW)
intR = 0.06
numPay = 12

' how much is the plant going to cost to construct?
plantCost = 125000000 '$

' add the plant cost to the total cost
cost = cost + plantCost

' calculate the amortized price per kWh
moPay = Pmt(intR / numPay, (projectLife * numPay), cost, 0, 1) _
* (-1)
annPay = numPay * moPay
amortize = annPay / energy
End Function
Public Sub cmdClear_Click()
    'clears the data
    Call clearData
End Sub

Function getEff(temp As Double) As Double
    'calculates the generator efficiency
    getEff = (0.0005 * temp) + 0.032
End Function

Public Sub clearData()
    Columns("A:F").Select
    Selection.ClearContents
    Range("A1").Select
End Sub

Public Function wellLife(energy As Double, minTemp As Double, mass As Double, heatCapacity As Double)
    'applies Newton's Law of Cooling for a geothermal well
    Dim currentTemp As Double
    Dim stepSize As Double
    Dim t As Double
    Dim exponent As Double

    exponent = 0.003 'the rate of cooling exponent
    stepSize = 0.01 'years
    t = 0

    currentTemp = energy / (heatCapacity * mass)

    'has the temperature of the well reached the
    'abandonment temperature?
    Do While (currentTemp > minTemp)
        'get the current energy of the reservoir
        currentEnergy = energy * Exp(t * -exponent)

        'calculate the current temperature from the
        'current energy content
        currentTemp = (currentEnergy / (heatCapacity * mass))
        t = t + stepSize
    Loop

    'return the final well life
    wellLife = t
End Function