A PRELIMINARY FEASIBILITY STUDY OF GEOTHERMAL AND MINERAL EXCTRACTION APPLICATIONS OF HYDROCARBON WELLS

A Thesis in

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by

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ABSTRACT

Oil and gas production technology has steadily evolved over the past 150 years. As commodities, oil and gas play important roles in both US and worldwide markets and are often viewed as critical economic drivers and assessment tools of the marketplace. Even though almost all local communities are in some way dependent upon oil and gas resources, there are many variables that contribute to the uncertainty of these commodities such as exploitation dynamics (e.g. technological, production, and cost factors), international law and trade factors, and local legislation factors (national and below). Factors such as these can make venture investment risky. The market, being dynamic, can quickly create constraints for new ventures and are often difficult to predict. The decline of oil and gas prices over the past year has jeopardized newer oil and gas technologies that rely on higher commodity prices to maintain a profit. The newly developed plays of the Marcellus and Utica Shales are examples of this phenomena. Oil and gas are limited resources; therefore, the price will continue to climb at some point. However, in the short run as prices fluctuate, companies will enter and exit based on technology and commodity price. This same phenomenon occurs in traditional mining with both the resources and technology. Traditional mining is much older than oil/gas mining and the technological growth has not been quite as rapid. Resources, however, are becoming more difficult to exploit as they are also limited. Many of the concentrated resources currently mined will at some time transition to a cut-off value too low for traditional mining methods to be used. Alternatives to traditional mining are already being developed and studied in an effort to mitigate the mentioned future issues of limited high grade ore. Both traditionally mined and oil and gas commodities attempt to maximize the resources available within the respective reserves. This thesis explores the potential of utilizing oil and gas resources to their fullest extent. Additional revenue that can be made from an oil or gas well will help mitigate risks associated with development and investment. Developing technologies to build on already available infrastructures will also potentially mitigate substantial investment costs for subsidiary technologies as well as ancillary environmental issues. Overall this thesis examines the feasibility of retrofitting Marcellus and Utica gas wells into geothermal wells and the potential of utilizing oil and gas wells as sources of traditionally mined materials.
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CHAPTER ONE
INTRODUCTION

1.1. Background

Oil and gas production technology has steadily evolved over the past 150 years. As commodities, oil and gas play important roles in both the US and worldwide markets as it is often viewed as a critical economic driver and assessment tool of the marketplace. Even though almost all local communities are in some way dependent upon oil and gas resources, there are many variables that contribute to the uncertainty of these commodities such as exploitation dynamics (e.g. technological, production, and cost factors), international law and trade factors, and local legislation factors (national and below). Factors such as these can make venture investment risky. The market, being dynamic, can quickly create constraints for new ventures and are often difficult to predict. Currently, oil and gas production is being hindered by uncertainties related to the Chinese market (i.e. lower demand) as well as consistent inexpensive production of oil in large reservoir regions (i.e. high production). The resulting decline of oil and gas prices over the past year has jeopardized newer oil and gas technologies that rely on higher commodity prices to maintain a profit. The newly developed plays of the Marcellus and Utica Shales are examples of this phenomena. Oil and gas are limited resources; therefore, the price will continue to climb at some point. However, in the short run as prices fluctuate, companies will enter and exit based on technology and commodity price. This same phenomenon occurs in traditional mining with both the resources and technology. Traditional mining is much older than oil/gas mining and the technological growth has not been quite as rapid. Resources, however, are becoming more difficult to exploit as they are also limited (especially certain resources). Many of the concentrated resources currently mined will at some time transition to a cut-off value too low for traditional mining methods to be used. Alternatives to traditional mining are already being developed and studied in an effort to mitigate the mentioned future issues of limited high grade ore. Both traditionally mined and oil and gas commodities attempt to maximize the resources available within the respective reserves. This thesis explores the potential of utilizing oil and gas resources to their fullest extent. Any additional revenue that can be made from an oil or gas well will help mitigate risks associated with development and investment. Developing technologies to build on already available infrastructures will also potentially mitigate substantial investment costs for
subsidiary technologies as well as ancillary environmental issues. This thesis examines the feasibility of retrofitting Marcellus and Utica gas wells into geothermal wells and the potential of utilizing oil and gas wells as sources of traditionally mined materials.

1.2. Geothermal Energy from Oil and Gas Wells

Renewable energy resources have gained public interest and become more recognized in recent years due to both the environmental and future cost benefits associated with them. Geothermal power production is a steadily increasing source of renewable energy production in the US. Largescale geothermal power plants are presently limited to geographic regions that overly shallow, hot magmatic pockets and require high initial capital costs. One of the major costs associated with these geothermal power plant developments is the costs to drill and install the wells. It is a tremendous risk to take on these geothermal endeavors, and the wells themselves can be one of the sources of greatest financial risk. Because of the investment risk associated with these projects, they are typically placed in regions of greatest potential as risk is minimized. While this approach is indicative of largescale operations, it may be possible for small scale operations to be taken on with minimal risk by capitalizing on other resources and infrastructures already developed for another purpose or industry sector. Geothermal power production from abandoned oil wells has been proposed and theoretically demonstrated [1, 2, 3]. Because the wells already exist, the expenses associated with well development are not required. This mitigates risk associated with the cost of drilling and allows some risk or cost to be transferred to other aspects of the operation. In the case of smaller scale operations developed in pre-established infrastructures, some of the mitigated risk and costs is passed on to a lower energy output; these regions are typically associated with a thermal gradient range that is much more narrow than those in large scale operations. As a result, less energy is developed from each well, but the cost for retrofitting the well into a geothermal well is much lower than those costs associated with full scale geothermal power plant investments.

Pennsylvania is in initial phases of developing gas wells and associated infrastructure for the Marcellus and Utica Shale plays. Oil prices are falling and are projected to continue this trend. These falling prices pose difficulties in maintaining profitable margins since the drilling and fracturing technologies used for extraction are expensive. These technologies are economically
viable mostly due to the relatively high oil prices experienced over the last several years. Furthermore, “fracking” has gained public dissatisfaction and given the industry a negative perception. Both of these issues could be offset by harvesting geothermal energy from spent, underperforming, or dry wells. Geothermal energy would enable wells to produce revenues after gas production cessation or from dry wells. It would also assist in turning the public focus from fracking to sustainability. Chapter two presents an assessment of potential harvesting of geothermal energy from gas wells in the Marcellus and Utica Shale plays in Pennsylvania.

1.3. Metal and Mineral Mining from Oil and Gas Wells
As previously stated, the risks and capital costs for the development of geothermal power plants are extensive. Electrical generation is the predominant and often only source of revenue for geothermal power plants. Scaling of mineral constituents within the brine has been known to be a source of significant issues for geothermal power plants-particularly the silica. The range of silica solubility typically falls into the range that the geothermal brine for geothermal power exists. As water temperature increases, silica is taken into the system. Consequently, as the temperature and pressure drops, silica precipitates back out, causing silica to scale onto the pipes and power plant equipment. Furthermore, the amount of heat that can be drawn out of the brine for power production is limited by this phenomenon, limiting the lower temperature at which water can be re-injected [4, 5, 6]. By controlling and manipulating the physical and chemical parameters of the brine, metal/mineral constituents can be precipitated out [7]. Silica was the initial target due to the aforementioned reasons. Additional metals were subsequently examined for the potential of extraction, raising the question of whether valuable metal/mineral constituents could be economically extracted for additional revenues [4, 8, 9]. Numerous investigations have been conducted in an effort to answer this question, and it appears that this technology may be feasible and profitable for select minerals and metals. Simbol Incorporated, a California based sustainable materials technology company, is developing plans to mine 15,000 metric tons of lithium annually from California geothermal brines [10]. This general concept may also be applied to oil and gas brines depending on brine composition. As industry continues to develop technology for this new type of mining, it is prudent to develop economic tools to assist in minimal risk implementation of new geothermal mining operations. Chapter three further explores the current developments of this
novel mining technology and posits a series of equations that can be utilized to appraise the economic feasibility of mineral extraction from a localized brine.

1.4. Thesis Organization

This thesis is organized into five chapters. This first chapter serves as an introduction and demonstrates how the various subparts of the thesis are related. The second chapter focusses on the feasibility of harnessing geothermal energy from nonproducing oil and gas wells. More specifically it characterizes the Utica and Marcellus Shales with respect to their abilities to facilitate potential geothermal energy with wells within Pennsylvania. The third chapter transitions to an assessment of metal and mineral mining feasibility from geothermal brines and to a lesser extent from oil and gas brines. This chapter includes the development of an equation set that enables a cut-off concentration (similar to cut-off grade) to be established for profitable mineral exploitation from brines. Both chapters two and three were developed and initially written for potential peer-reviewed publication, hence the reason for individual chapter structure within this thesis. Chapter four was initially developed as a proposal. While not awarded, the framework of the proposal was included since some of the information builds on previous chapters work with an emphasis on Rare Earth Elements (REEs). Chapter five provides a summary the thesis, highlights key results and conclusions, and addresses future work that can build upon the results of this thesis.
References


GEOTHERMAL ENERGY AS A SECONDARY ENERGY SOURCE FROM PENNSYLVANIA NATURAL GAS WELLS

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Abstract
The natural gas shale boom in Pennsylvania has enabled thousands of new deep wells to be drilled. Oil prices, typically volatile, have been steadily declining since June 2014. Some economists are speculating whether the industry will be able to continue to produce tight gas if oil prices continue to decline. In order to offset risk from declining profits due to falling oil prices and from future market fluctuations, it is proposed that geothermal energy be considered as a potential energy source for future additional revenues once wells no longer produce. This chapter assesses the potential of extracting geothermal energy from natural gas wells and classifies potential energy extraction groups.

2.1. Introduction
Pennsylvania is in initial phases of developing natural gas wells and associated infrastructure for the Marcellus and Utica Shale plays. Oil prices are falling and are projected to continue this trend. These falling prices pose difficulties in maintaining profitable margins since the drilling and fracturing technologies used for extraction are expensive. These technologies are economically viable mostly due to the relatively high oil prices experienced over the last several years. “Fracking” has gained public dissatisfaction and given the industry a negative perception. Both of these issues could potentially be partially mitigated by harvesting geothermal energy from spent, underperforming, or dry wells. Geothermal energy would enable wells to produce revenues after natural gas production cessation or from dry wells. It would also assist in turning the public focus from fracking to sustainability. This paper presents an assessment of the potential harvesting of geothermal energy from natural gas wells in the Marcellus and Utica Shale plays in Pennsylvania.
2.1.1. Background

Pennsylvania has been experiencing a boom in natural gas extraction from the Marcellus and Utica Shale plays (Figure 1). This recent oil and gas boom, due to the new technological developments of hydraulic fracturing, is one of several factors contributing to a decrease in oil prices, and this decrease is causing financial stability issues for the oil and gas industry. In December 2014, the national average price for gas in the U.S. fell below $3 a gallon for the first time in three years and has recently fallen below $2 a gallon in several US regions. Many in the industry question whether the oil and gas industry will be able to continue operations in the Marcellus and similar shale plays due the low prices the industry has induced. If prices fall low enough for a substantial time period, extracting these resources will become uneconomical. If these sustained prices inhibit the industries expected growth, only “sweet spots” that are economical will be drilled and fractured. Additionally, profitability is further constrained by overestimates of amounts of natural gas that can be recovered from the major shale plays [1]. Economic swings in the oil and gas industry will determine which resources can be extracted. Secondary sources of revenue from geothermal resources through these wells may increase the amount of gas resources that could be recovered as well as offset losses caused by lags between market prices and well installation.

Figure 1. Map of Unconventional Wells in Pa Marcellus Shale. [Image]. Obtained from http://marcellus.psu.edu/images/staticMap2013.jpg.
Geothermal power is an advantageous and attractive energy source due to its reliable, renewable, and clean characteristics. Furthermore, it has the potential to become the most economical thermal fuel type for direct heating and power generation [2]. Geothermal energy is classified by its source temperature (Table 1). Dry steam, flash, and binary power plants have been in use for many decades in the western US where the geothermal gradient is high due to magmatic pockets lying relatively close to the surface. Enhanced Geothermal Systems (EGS) are typically utilized for extracting energy from high temperature regions that have low permeability and/or low fluid flow. Applications of this technology have been proposed for heating in New York and Pennsylvania utilizing low-temperature geothermal energy [3]. Over the last few decades, there has been increased research and development on low temperature (<150° C) geothermal energy, affording additional geographic locations the opportunity to extract and use geothermal energy. Geothermal heat pumps have become economically feasible in the last two decades for much of the US, enabling access to low temperature geothermal resources. This technology typically capitalizes on shallow geothermal energy relatively close to the surface.

**Table 1. Geothermal energy types by temperature.**

<table>
<thead>
<tr>
<th>Geothermal Energy Type</th>
<th>Temperature Range (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geothermal Power-Dry Steam</td>
<td>&gt;390</td>
</tr>
<tr>
<td>Geothermal Power-Flash</td>
<td>180-390</td>
</tr>
<tr>
<td>Geothermal Power-Binary</td>
<td>80-390</td>
</tr>
<tr>
<td>Geothermal Heat Pumps and EGS</td>
<td>&gt;7</td>
</tr>
<tr>
<td>Low Temperature Geothermal Resources</td>
<td>&lt;150</td>
</tr>
</tbody>
</table>

One of the greatest capital costs associated with geothermal energy is the costs to drill and install the well. In an effort to minimize or offset capital costs associated with drilling, geothermal power production from abandoned oil wells has been proposed and theoretically demonstrated [4, 5, 6, 7]. This technology would increase economic potential since costs for drilling the well would not be incurred for the geothermal aspects of production. Based on data from 2009, typical well costs for Marcellus Shale depths are typically greater than $2,000 per meter and can exceed $10 million for a completed well [8]. Augustine and Falkensten proposed that technology could be developed for the coproduction of oil/gas production and geothermal energy [9]. Companies operating such
wells could offset operating costs, minimize financial risks, and increase profits from such wells by either coproduction from active wells or by electricity generation from spent or dry wells. It should be noted also, that a typical proper abandonment, in accordance with regulations, of a well costs approximately $34.45 per meter [10]. This cost could be used for the expenses incurred from retrofitting spent wells with this technology.

2.1.2. Objective
The objective of this research is to demonstrate by theoretical methods the potential in which Marcellus and Utica Shale wells can be used for geothermal energy and to categorize the types of geothermal energy that are most feasible. This geothermal energy is the upper boundary of what is available for extraction. Further evaluation and research will have to be conducted to hone in on the actual energy extraction of specific applications.

2.2. Methodology
In order to determine the potential of extracting geothermal energy from Marcellus and Utica Shale wells, three main stages were conducted with each stage feeding information gained from that stage into the subsequent stage. These three stages consisted of a spatial correlation stage, a geothermal gradient and temperature assignment stage, and a thermodynamic fluid model stage. Figure 2 shows a flowchart of the research method stages and associated inputs.

![Flowchart of research methods and associated inputs.](image)

**Figure 2.** Flowchart of research methods and associated inputs.
2.2.1. Spatial Correlation Stage

For the first stage, the spatial correlation stage, three main information groups were analyzed and combined in ArcGIS to provide assumed well depth data that could be used for stage two including: geographic well data, Marcellus and Utica Shale data, and mean annual surface temperature data. Well position data for Marcellus and Utica Shale wells were obtained from a Pennsylvania Department of Environmental Protection (PADEP) public database [11]. This database publishes digital data and includes a wide array of functions and sort filters that can be used for accessing oil and gas well information. The spatial location (i.e. latitude and longitude) of a total of 9,163 Marcellus Shale wells and 126 Utica Shale wells was filtered and exported to Microsoft Excel. Only active wells were filtered for this research, but this process could be expanded to include abandoned, dry, and other non-active well types. A unique well identification number was generated for each well in order to track and manage well data through this project. The well identification numbers consist of consecutive integer values from 10,001 to 19,289. Associated well temperature and depth values were not given with the PADEP data. Depth values for the wells were not available from the PADEP database; therefore, each well was assigned an assumed depth (feet below ground surface) that reflected the depth of the base of its respective shale play minus (bringing depth point upwards) one half the distance of its initial (lowest) thickness value. This distance was chosen because the region of the shale in which the horizontal portion of the well is drilled is typically just above the base of the formation. Marcellus and Utica Shale geospatial data was provided by the Marcellus Center for Outreach & Research (MCOR) [12] to create two average depth shapefiles-one for the Marcellus Shale play and one for the Utica Shale play. This process consisted of merging the depth to shale and thickness of shale data (Figure 3) to provide a shapefile depicting the depth to midpoint of the shale vertical boundaries spatially. It can be seen from Marcellus images in Figure 3 that the depth to formation ranged from 2,000 to 9,000+ feet in 1,000 foot increments, and the thickness ranged from 0 to 350 feet in 50 foot increments. Even though the shapefiles have a semi-staggered resolution, this data is the best that was available for this project. Resolution issues will be described in more detail in the results and discussion section.

Once this shapefile was created for each shale play, each of shale play shapefiles were merged with three shapefiles containing thermal data; these values were required inputs for the Cornell Python
ArcGIS was then used to assign a depth (Z; ft), a mean annual surface temperature (°C), a surface heat flow (W/m²), and a basement depth (ft) for each unique well identification number.

Figure 3. Clockwise from top left: maps of depth to Marcellus Shale base, depth to Utica Shale, Marcellus Shale thickness, and Utica Shale thickness. [Image]. Obtained from http://marcellus.psu.edu/images/UticaDepth.gif.

2.2.2. Geothermal Gradient and Temperature Assignment Stage

For stage two data, the geothermal gradient and temperature assignment stage, borehole temperature values were assigned to each well by running stage one results through a thermal model developed by Cornell University for the Appalachian Basin. This thermal model was created for the purpose of showing the thermal field properties of New York, Pennsylvania, and West Virginia. While many geothermal gradient maps and local geothermal gradient equations exist, most have fairly low resolution and/or accuracy. For example, Figure 4 shows a map of the US with its geothermal characteristics. General warm and cool spots are visible in Pennsylvania, but
the resolution is too low to see localized “hot” spots that may exist. Figure 5 shows the major oil and gas shale plays in the continental US. While this paper is focused on the Marcellus and Utica Shale plays, there are several other areas of the US that this proposed application may be applicable.


Figure 5. Map of major oil and gas shale plays in the Conterminous United States. [Image]. Obtained from http://www.lib.utexas.edu/maps/united_states/united_states-shale_plays-2011.pdf.
In an effort to identify localized “hot” spots, the thermal model created by Cornell University was used since it provides the finest resolution currently available. The Cornell model consists of a program developed in Python 2.7.9 that references the following data: correlation of strategic units in North America, sediment thickness, a Rome Trough identifier, average annual ground and surface temperature, borehole temperature correction, borehole temperature, drilling fluid, neighboring well drill data, mantle heat flow, and sediment radiogenic heat generation. This model essentially uses geological and thermal data from borehole and surface data to create a geothermal gradient profile at any region within Pennsylvania. By feeding the model geographic and well parameters, a localized geothermal gradient and borehole temperature is determined for each unique well identification number.

2.2.3. Thermal Model Energy Loss Calculation

Previous Work
Previous studies related to extracting geothermal energy from oil and gas wells typically utilize the double pipe heat exchanger model as the primary method for evaluating feasibility. One of the major reasons for targeting pre-established infrastructures (i.e. wells) for geothermal energy is that much of the capital cost associated with traditional geothermal wells (from drilling and well completion) can be avoided. By inserting an inner insulator pipe (or a pipe with insulation) inside of the well, fluid can flow down through the annular space between the well and insulator pipe. This fluid warms up as it flows downward (due to the geothermal gradient) and is recirculated back to the surface through the central insulator pipe after it reaches the bottom of the well. At the surface, heat energy is extracted and the fluid is reinjected into the annular region of the wellhead. This continuous closed loop process allows for relatively inexpensive continuous energy. Several thermodynamic models for the double-pipe heat exchanger and heat transfer in a well have been proposed (Davis and Michaelides [4], Bu et al. [5], Bu et al. [6], Kujawa et al. [7], Kujawa and Nowak [13], and Kwon [14]). The models proposed by Davis and Michaelides, Bu et al., and Bu et al. consider the case for retrofitting abandoned oil and gas wells for geothermal energy by using a double pipe heat exchanger mechanism. Nowak and Kujawa, and Kujawa et al. propose the double pipe heat exchanger concept in lieu of traditional production and injection wells in order to save capital costs for future geothermal well investments. While these cases are good for modeling abandoned oil wells, they do not appropriately model unconventional (tight gas or hydraulically
fractured) gas wells since unconventional gas wells contain a lateral portion at the bottom. Furthermore, unconventional gas wells have a radius that becomes incrementally smaller with depth. Since the purpose of this chapter is to show geothermal energy feasibility, a modified version of the double pipe heat exchanger is proposed. For this model, an insulator pipe of uniform diameter is used as the inner pipe in which heated fluid moves upward. Fluid in the exterior region is treated as a reservoir that flows downward and is in thermal equilibrium with the formation. The lower boundary where fluid transitions from downward to upward flow is treated such that the boundary temperature reaches borehole temperature for both the downward and upward flow. This assumption is made since the lateral portion could be treated as a reservoir in thermal equilibrium with its surroundings. Injected fluid into the exterior boundary of the wellhead was assumed to be average annual surface temperature. With these assumptions, the problem can now be assessed as a thermal loss for fluid flowing through a pipe. Kwon proposes such a model for evaluating thermal losses of a fluid in a pipe. This model utilizes a procedure that subdivides a pipe into portions of length (L; m), and then calculates the thermal loss through that pipe by iterating temperature loss through each pipe section of length (L; m).

2.2.4. Well Constraints

Figure 6 shows a schematic of the modified double-pipe heat exchanger and heat transfer in a well. Figure 7 shows a schematic of a typical Marcellus Shale gas well. Nonproducing wells would be retrofitted into geothermal wells by inserting an insulator pipe through the full length of the vertical portion of the well. The well can either be sealed at the horizontal portion of the well, or can be open and fitted with piping such that mixing is induced and retention time of the working fluid in the horizontal region is maximized. In either case, the design should be such that fluid temperature has adequate time to equilibrate with the formation temperature. A working fluid would be injected through the outer pipe region where it would increase in temperature as it flows downward. Temperature would reach a maximum at the bottom where the flow will then be routed upward through the insulated inner pipe. Some temperature losses will exist from the inner to the outer pipe but will be minimized by using a thermally resistive insulator pipe. At the surface, thermal energy will be extracted from the working fluid will and then be re-injected back into the well for recirculation.
Figure 6. Schematic of well with section showing one subset of pipe length L.

Insulator pipe diameter is restricted to a maximum value lower than smallest inner diameter of the well (approximately 5.5 inches). Future models can incorporate a varying pipe diameter along its length (vertically). If the lateral portion of the well is treated as a reservoir, and the retention time is long enough, working fluid in velocities and volumetric flow in the insulator pipe and annular space can be maximized such that maximum energy extraction can occur at the surface. In this case working fluid velocity is then a function of retention time in the reservoir and thermal fluid properties for thermal considerations (the fluid dynamics must also be considered to see if it is a limitation).
2.2.5. Equations and Calculation Procedure

2.2.5.1. Equations

This heat transfer model and set of equations assumes steady state conditions and single phase fluid flow with no phase change. The annular regions of the pipe system is assumed to be in thermal equilibrium with the surrounding rock (geothermal gradient of local region equals that of the fluid in the annular space). The model subdivides the total well length (Z) of a well into 100 units and iteratively calculates the temperature loss through each successive section. Figure 8 shows a distinct interval with the boundary conditions, input fluid temperature, and output fluid temperature. Boundary temperature for the Nth interval is given as the average temperature of the
local geothermal gradient in contact with that boundary. The initial temperature is set equal to the borehole temperature (Stage 2 results), and the injected fluid temperature is set equal to the surface temperature. These assumptions yield the maximum temperature difference that can be realized for a given well.

Figure 8. Schematic of interval block and boundary conditions.

Pipe Geometry
Equations 1 and 2 provide the inner (1) and outer (2) surface areas of the insulator pipe for a given pipe interval.

\[ SA_I = \pi (D_I)(L) \]  
\[ SA_O = \pi (D_O)(L) \]

where
\[ SA_I = \text{inner surface area (m}^2\text{)} \]
\[ SA_O = \text{outer surface area (m}^2\text{)} \]
\[ D_I = \text{inner insulator pipe diameter (m)} \]
\[ D_O = \text{outer insulator pipe diameter (m)} \]
\[ L = \text{pipe length of one interval (m)} \]
Logarithmic Mean Area of Heat Transfer

Equation 3 gives the logarithmic mean area of heat transfer. The logarithmic mean area enables the heat transfer properties to be determined for systems with cylindrical geometries.

\[
AM_{HT} = \frac{(SA_O - SA_I)}{\ln \left(\frac{SA_O}{SA_I}\right)}
\]

where

\(AM_{HT}\) = Logarithmic mean area of heat transfer (m²)

Thermal Insulance

The thermal resistance of the insulating pipe is given by Equation 4. This thermal insulance provides a measure of thermal resistance per unit area of the insulator pipe.

\[
R_I = \frac{I_T}{(k)(AM_{HT})}
\]

where

\(R_I\) = insulation pipe thermal resistance (W/m²°C)

\(I_T\) = insulated pipe thickness (m)

\(k\) = thermal conductivity (W/m°C)

Fluid Characteristics

The mass of fluid per pipe length is given by Equation 5.

\[
M = (\rho)(\pi)\left(\frac{D_I}{2}\right)^2 (L)
\]

where

\(M\) = mass of fluid per unit L length (kg)

\(\rho\) = density of fluid (kg/m³)
The exit fluid temperature for a given pipe interval is given by Equation 6.

\[ T_E = T_S - \frac{(T_M - T_R)(t)}{(M)(C)(R)} \]  

(6)

where
\( T_E \) = ending fluid temperature of pipe interval (°C)
\( T_S \) = surface temperature (°C)
\( T_M \) = mean fluid temperature of pipe interval (°C)
\( T_R \) = rock temperature surrounding pipe interval (°C)
\( t \) = time for fluid to travel distance L (sec)
\( C \) = specific heat of fluid (Joules/kg°C)

The mean fluid temperature (TM) for a given pipe interval is given by Equation 7.

\[ T_M = \frac{2(M)(C)(R)(T_S) + (T_R)(t)}{2(M)(C)(R) + t} \]  

(7)

2.2.5.2. Calculation Procedure

Surface temperature, borehole temperature, and well depth from stage two served as inputs to the calculation. Additionally, insulator pipe geometry and characteristics, and fluid characteristics were added as inputs. Table 2 shows the insulator pipe and working fluid inputs for the calculation. For this study, polystyrene was selected as the material for the insulator pipe and water was selected for the working fluid. Polystyrene was chosen as the pipe material because of its favorable thermal characteristics and has been used by other researchers modeling double pipe heat exchanger for geothermal energy from abandoned oil and gas wells [4]. Water was chosen as the working fluid since it is relatively inexpensive, adequately available, and little to no additional work other than the installation of the insulator pipe must be performed to a well for utilizing water as the working fluid. Other working fluids may be better suited for this application from a thermodynamic standpoint, but practical considerations must be made when dealing with other working fluids (e.g. sealing the bottom portion of the well, economics, environmental concerns,
etc.). Additional working fluids is a topic that can be considered in future work for this specific application but is not within the scope of this chapter’s objective.

### Table 2. Input parameters for insulator pipe and working fluid.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Units</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>k</td>
<td>0.027</td>
<td>W/m°C</td>
<td>polystyrene</td>
</tr>
<tr>
<td>D_I</td>
<td>0.0762</td>
<td>m</td>
<td>inner diameter of insulator pipe</td>
</tr>
<tr>
<td>D_O</td>
<td>0.127</td>
<td>m</td>
<td>outer diameter of insulator pipe</td>
</tr>
<tr>
<td>Q_F</td>
<td>varied</td>
<td>l/s</td>
<td>working fluid upward flowrate</td>
</tr>
</tbody>
</table>

A simple program in Microsoft Excel was made to take the input parameters and apply them to the equations previously shown. The program divided the well length (Z) into 100 portions and calculated the exit temperature across each block as described above. Additionally, a macro was created to iterate the input values of each unique well identification number through this program. For each unique well, a final output temperature was given. The difference between surface and final output temperature is the maximum temperature differential that can be realized from a given well. In order to assess useful work, maximum power in kilowatts (kW) was calculated for each unique well.

### 2.3. Results and Discussion

#### 2.3.1. Spatial Correlation Results

The spatial correlation procedure resulted in an estimated (i.e. assumed) well depth, based on the depth to and thickness of the shale formation, for each of the identified 19,289 Marcellus and Utica shale wells. Figure 9 and Table 3 depict the main characteristics of these results. Values range from 769.6 meters to 4,091.9 meters with a mean value of 2,106.8 meters.
Figure 9. Histogram of spatial correlation results showing number of wells for a given depth range.

Table 3. Summary statistics for Figure 8.

<table>
<thead>
<tr>
<th>Statistic</th>
<th>Value (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>2106.8</td>
</tr>
<tr>
<td>Standard Error</td>
<td>3.3</td>
</tr>
<tr>
<td>Median</td>
<td>2065.0</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>318.1</td>
</tr>
<tr>
<td>Sample Variance</td>
<td>101218.8</td>
</tr>
<tr>
<td>Range</td>
<td>3322.3</td>
</tr>
<tr>
<td>Minimum</td>
<td>769.6</td>
</tr>
<tr>
<td>Maximum</td>
<td>4091.9</td>
</tr>
<tr>
<td>Count</td>
<td>9289</td>
</tr>
</tbody>
</table>

Figures 10 shows Utica and Marcellus well depths plotted as a function of unique well identification number. Figure 11 shows Utica and Marcellus well depths plotted as a function of decreasing depth. Ten distinct bands can be seen in Figure 10, and multiple decreasing steps are visible in Figure 11. These two observations are manifestations of the data resolution limitations. The Marcellus shapefiles categorized depth values at 1,000 foot increments and thickness values at 50+ foot increments. The Utica shapefiles categorized depth values at 2,000 foot increments and thickness values at 100+ foot increments.
Since depth values were calculated as midpoint values of the vertical portion of their respective shale plays, the error for any calculation based on these calculated values will have a maximum error of ± one half the thickness range plus one half of the initial depth range value of each respective shale play. The maximum error for a Utica well depth is ±320 meters, and the maximum error for a Marcellus well depth is ±160 meters (Table 4).
**Table 4.** Shale depth, thickness, and error values.

<table>
<thead>
<tr>
<th>Shale Play</th>
<th>Depth (ft)</th>
<th>Thickness (ft)</th>
<th>Maximum error from center value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Utica</td>
<td>2000</td>
<td>100</td>
<td>±1,050 feet ±320 meters</td>
</tr>
<tr>
<td>Marcellus</td>
<td>1000</td>
<td>50</td>
<td>±525 feet ±160 meters</td>
</tr>
</tbody>
</table>

Figure 12 shows the Utica well depth plotted as function of sorted well number of decreasing depth. This plot clearly shows the resolution issue described above. It can be seen that the error bars of each band cover the portion between consecutive bands such that the whole vertical spectrum of Utica well depth values are covered, confirming the resolution error. Figure 13 shows the same error analysis for the Marcellus wells but is more difficult to observe due to the high number of data points. These errors are carried through the subsequent sections and are included the final results.

![Utica Well Depths with Error Bars](image)

**Figure 12.** Utica well depths plotted as a function of decreasing depth with error bars.
Figure 13. Marcellus well depths plotted as a function of decreasing depth with error bars.

2.3.2. Geothermal Gradient and Temperature Assignment Stage Results

Thermal model temperature calculation results show the borehole temperature values for each of the 19,289 well depth values for each of the unique well identification numbers. Figure 14 shows a histogram of borehole temperatures, and Table 5 provides a summary of the major statistics characterizing these values. The mean borehole temperature value is 57°C. The minimum and maximum borehole temperature values are 25°C and 105°C respectively. Figure 15 shows the range of error values for all unique well identification numbers. The values are plotted such that each point represents the maximum and minimum borehole temperature error for a given unique well identification number. The errors range from 2°C to 14°C for both the maximum and minimum temperature errors with the bulk of the error partitioned between 2°C and 8°C. Figure 16 shows borehole temperature values plotted as a function of well depth with associated temperature and depth error bars shown. Although temperature values appear to reach a maximum around 100°C, more data points for wells greater than 3,000 m are needed to accurately assess deeper wells. High temperature values (100°C) are realized in wells as shallow as 2,300 m, and well depths of 1,200 m are where borehole temperatures begin to appreciably rise in temperature. The vertical range in temperature variability for a given well depth is most likely due to the geologic factors. Wells of a given depth are scattered throughout Pennsylvania and are not geographically co-located.
Figure 14. Histogram showing borehole temperature values of all wells.

Table 5. Summary statistics for Figure 13.

<table>
<thead>
<tr>
<th>Statistic</th>
<th>Value (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>57.1</td>
</tr>
<tr>
<td>Standard Error</td>
<td>0.1</td>
</tr>
<tr>
<td>Median</td>
<td>55.4</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>11.1</td>
</tr>
<tr>
<td>Sample Variance</td>
<td>124.3</td>
</tr>
<tr>
<td>Range</td>
<td>79.8</td>
</tr>
<tr>
<td>Minimum</td>
<td>25.2</td>
</tr>
<tr>
<td>Maximum</td>
<td>105.1</td>
</tr>
<tr>
<td>Count</td>
<td>9289</td>
</tr>
</tbody>
</table>
Figure 15. Temperature error for all wells.

Figure 16. Borehole temperature vs. well depth with associated temperature and depth errors.

Figure 17 shows a histogram borehole temperature to well depth ratios. The larger the ratio of borehole temperature to well depth, the better the assumed energy assuming all other parameters are equal. This relationship can be considered as the temperature gradient through the length of the pipe. Most wells have a gradient between 0.018°C/m and 0.019°C/m.
2.3.3. Thermal Model Energy Loss Calculation Results

Thermal model energy loss calculation results show the maximum amount of theoretical power output, or thermal power, that a well is capable of producing. Figure 18 shows a histogram of maximum available thermal power from all wells, and Table 6 provides the summary statistics associated with these values. The mean thermal power available is 2.4 MW. The minimum and maximum amounts of thermal power available are 0.7 MW and 5.0 MW respectively. Figure 19 shows the maximum amount of thermal power of each well sorted by order of decreasing magnitude with associated upper and lower error values. The error values appear as bands bounding the upper and lower sides of the power potential because of the high number of data points.

Figure 20 shows a histogram of the fluid temperature values that exit the wellhead at the surface for all wells. Table 7 summarizes the statistics associated with the Figure 20 histogram. The average fluid temperature value that exits the wellhead is 56.9°C. The minimum and maximum values of wellhead exit fluid temperatures are 25.2°C and 104.7°C respectively. While a small fraction of wells appear to be suitable for potential geothermal power applications (433 wells greater than 80°C), the majority appear to be most suitable for low temperature geothermal applications such as direct heating (less than 80°C).
Figure 18. Maximum thermal power available from all wells.

Table 6. Summary statistics for Figure 17 values.

<table>
<thead>
<tr>
<th>Statistic</th>
<th>Value (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>2.4</td>
</tr>
<tr>
<td>Standard Error</td>
<td>0.0</td>
</tr>
<tr>
<td>Median</td>
<td>2.3</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>0.6</td>
</tr>
<tr>
<td>Sample Variance</td>
<td>0.4</td>
</tr>
<tr>
<td>Range</td>
<td>4.3</td>
</tr>
<tr>
<td>Minimum</td>
<td>0.7</td>
</tr>
<tr>
<td>Maximum</td>
<td>5.0</td>
</tr>
<tr>
<td>Count</td>
<td>9289</td>
</tr>
</tbody>
</table>
Figure 19. Maximum amount of thermal power of each well sorted by order of decreasing magnitude with associated upper and lower error values.

Figure 20. Temperature values of working fluid exiting the wellhead at surface.
Table 7. Summary statistics for Figure 19.

<table>
<thead>
<tr>
<th>Statistic</th>
<th>Value (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>56.9</td>
</tr>
<tr>
<td>Standard Error</td>
<td>0.1</td>
</tr>
<tr>
<td>Median</td>
<td>55.2</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>11.1</td>
</tr>
<tr>
<td>Sample Variance</td>
<td>123.1</td>
</tr>
<tr>
<td>Range</td>
<td>79.5</td>
</tr>
<tr>
<td>Minimum</td>
<td>25.2</td>
</tr>
<tr>
<td>Maximum</td>
<td>104.7</td>
</tr>
<tr>
<td>Count</td>
<td>9289</td>
</tr>
</tbody>
</table>

This study assumed a fixed insulator pipe diameter. Flowrate has an appreciable effect on temperature and power output. Figure 21 shows the effects of varying flowrate on output temperature and available power. Temperature values for this rose rapidly; power available increases linearly with flowrate. These two observations have significant implications on design criteria for a given well.

![Effects of Varied Flowrate](image)

Figure 21. Effects of varied flowrate on output temperature maximum thermal power.
Flowrate has appreciable influence on the temperature losses when all other parameters are held constant, and for the case of an already established well, most other parameters are relatively fixed or at least constrained. When utilizing an existing structure, any retrofitting must be done within the constraints of the well. This severely constrains insulator pipe thickness and inner diameter. These are the only other dimensional parameters that can be changed (k can potentially be increased but is only influenced dimensionally by insulator pipe thickness). Flowrate is the only factor that can be substantially varied. A minimum flowrate for a given design must be reached to minimize temperature losses (blue and orange lines in Figure 21). Increasing flowrate also increases total thermal power output. The limiting factor for this will be a function of fluid retention time in reservoir and reservoir size. Thermal power output at the surface is restricted to what can be provided to the reservoir. Aside from this restriction, a fluid moving at a faster rate will deliver energy to the surface at a faster rate; this is what is observed on the grey line in Figure 21.

One important note is that this paper treats the lateral portion of the well as a reservoir (the fracked region). Other double pipe heat exchangers that model oil and gas wells strictly account for temperature gains and losses through the vertical section of a traditional well. In these models the fluid temperature often fails to reach the borehole temperature because the low retention time of the fluid through the warmest portions of the well. This model assumes the retention time is long enough to allow the fluid temperature to reach (i.e. equilibrate with) borehole temperature. It also allows the fluid velocity to be maximized since the fluid is no longer relying on the thermal gradient for its added energy-it receives it in the reservoir. Maximizing fluid velocity decreases the temperature losses and yields higher available thermal power output.

The output temperatures of these wells are suitable for low temperature geothermal applications. Many of these wells are suitable for direct heat applications. The average house requires approximately 10 kW for heating. These values indicate that an average well can provide sufficient heat for 250 houses. These wells could also be used for industrial applications where heat is required for a production process. Many of the wells particularly in the Pittsburg region may be suitable for either domestic or industrial heating applications.
2.3.4. PA Shale Gas Infrastructure and Layout

Not only does the existing infrastructure for geothermal application cause reason for conducting this analysis, but the layout of the infrastructure itself acts as a force multiplier with respect to energy production. This section provides a general background on applicable infrastructure and layout and why it assists in potential feasibility.

Natural gas wells are drilled and occur in a layout such that multiple wells from a single pad reach out to pull gas from a series of grids surrounding the pad region. Figure 22 shows a schematic showing a series of grids sharing a common well pad. These grids are juxtaposed to similar grids and form a network similar to a chess board arrangement. A typical well will pull gas from a region approximately 300 m by 2,100 m (in plan view). A typical well pad has 4 to 8 wells networked to it.

Because of this arrangement, many options for geothermal energy can be applied. Here the most obvious are presented. One option is to utilize each well within each grid to extract energy and pass it to a common power tie on the well pad. This option would extract energy directly at the wellhead (inner pipe) and then immediately reinject the working fluid. Another option would be to tie all extraction wells (annular space) on a well pad together and use their combined fluids for energy extraction. This option would tie all extraction wells to a common conduit, extract the energy, then redistribute the working fluid back into the injection wells. A third option would be to combine all of the working fluid and continue passing it on through insulated pipe to a power plant. This option would utilize hundreds of grids along several lines to combine heated fluid (most likely water) for a power plant. The power plant would supply additional energy for final

Figure 22. Schematic of a series of grids feeding a well pad.
extraction. The goal of this option is to reduce the energy requirements for heating the working fluid (such as a coal or oil power plant). Injected working fluid would be passed to each well by a separate pipeline. Numerous other options can be developed from this infrastructure as well.

2.3.5. Energy Availability Analysis

Even though it has been established that a well can produce power from the aforementioned conditions, in order to perform a complete analysis, the amount of energy available as a resource must be evaluated; energy is being mined from the subsurface. Figure 23 shows a schematic of a vertical profile of a well grid and its associated energy.

![Schematic of a vertical profile of a well grid and its associated energy](image)

**Figure 23.** Schematic of a vertical profile of a well grid and its associated energy

As can be seen in Figure 23, thermal energy supplied to a well originates from one of three basic entities: heat generated from the mantle, radiogenic energy from within the rock within the profile boundaries, and thermal energy stored within the rock within the profile boundaries.
Mantle Heat
The heat flux generated from the mantle within this region is estimated to be 0.03 W/m² [15]. For each grid of size 300 m by 2,100 m (630,000 m²), approximately 18.9 kW is generated.

Radiogenic Heat
Within the boundaries of each grid, from the surface to the mantle, radiogenic heat is generated (particularly within the shales). For this calculation, the entire vertical profile was assumed to be shale in order to determine the maximum radiogenic heat component. The shale radiogenic heat generation was assumed to be 2.002 μW/m³ [16]. For a grid with a depth of 4,900 m, 6.2 kW is generated.

Stored Heat
The last component of heat energy is thermal energy stored within the rock. For this portion of the analysis the following equation is used:

\[ Q = (\rho_{\text{rock}})(V_{\text{rock}})(C_p)(T_2 - T_1) \]  

where

\[ Q \]  = heat stored (J)
\[ \rho_{\text{rock}} \]  = density of shale (kg/m³)
\[ V_{\text{rock}} \]  = volume of shale (m³)
\[ C_p \]  = heat capacity of shale of shale (J/kg°C)
\[ T_2 \]  = final temperature (°C)
\[ T_1 \]  = initial temperature (°C)

This procedure assumes that the entire unit equilibrates to ambient temperature (T₁) in order to assess the maximum case. The density of shale, \( \rho_{\text{rock}} \), was assumed to be 2,500 kg/m³ and the heat capacity of shale was assumed to be 0.84 J/kg°C [16]. For a given grid and its vertical profile, a total of \( 2.98 \times 10^{14} \) J of energy is available.

From these three sources, a total of 25,080 W of power is available as recharge—all other energy is purely mined from the stored energy within the rock. Figure 24 shows the power available for a
given lifespan of energy per 1 and 8 grid-spaces. Essentially, this shows how long a power plant can extract energy at a given power rating per number of grid-spaces. The number of grid-spaces providing power increases power by a factor equal to the number of grid-spaces.

![Graph of Power Available for a Given Lifetime per Grid-space](image)

**Figure 24.** Graph of Power Available for a Given Lifetime per Grid-space.

Table 8 shows a comparative chart of different power generators and their applications [17].

**Table 8.** A comparison of different power units and their applications [17].

<table>
<thead>
<tr>
<th>Units</th>
<th>Value</th>
<th>Example</th>
<th>Coal Equivalent</th>
<th>Power Application/Potential</th>
</tr>
</thead>
<tbody>
<tr>
<td>Watts</td>
<td>100</td>
<td>Typical Lightbulb</td>
<td>700 lbs</td>
<td>Small devices/appliances</td>
</tr>
<tr>
<td>Kilowatts</td>
<td>3</td>
<td>1 US home</td>
<td>4.7 tons</td>
<td>1 US home</td>
</tr>
<tr>
<td>Megawatts</td>
<td>2.5</td>
<td>Wind Turbine</td>
<td>8,750 tons</td>
<td>Hundreds to thousands of home (average turbine = 400 homes)</td>
</tr>
<tr>
<td>Gigawatts</td>
<td>2</td>
<td>Hoover Dam/Nuclear</td>
<td>7,000,000 tons</td>
<td>1.5 million+ homes</td>
</tr>
<tr>
<td>Terawatts</td>
<td>3.3</td>
<td>N/A</td>
<td>11,550,000 tons</td>
<td>2008 US consumption</td>
</tr>
<tr>
<td></td>
<td>16.5</td>
<td>N/A</td>
<td>57,750,000 tons</td>
<td>2008 World consumption</td>
</tr>
</tbody>
</table>

A few important conclusions can be drawn from this evaluation. Annual recharge rate governs the long term state of this energy source. At 25,080 Watts of generated energy, for every MW spent, 39.9 years will be required to renew the consumed energy from one grid-space; this is the only true renewable energy. If 1 MW was to be distributed over an area for recharge, it would require a region of 25.2 km² (6,227 acres).
Careful consideration regarding recharge and energy mining must be taken for establishing energy extraction sites as well as spacing between sites, and lifespans. Further research needs to be conducted to develop optimized grid-spacing and spacing between sites.

### 2.3.6 Precipitation Issues

Precipitation, also known as pipe scaling, has been quite problematic for the geothermal industry. This phenomenon occurs when mineral constituents within the brine precipitate out onto the inner pipe/equipment surfaces and leads to poor system performance. In some cases, precipitation is so great that pipe diameters converge to levels such that the infrastructure must be replaced (wells and piping). Precipitation can occur for many reasons and is explained in more detail in chapter 3. Much of the precipitation is a result of some major system change such as a significant changes in pH, temperature, or pressure. Greater changes often yield greater precipitation rates. Mineral constituents within the brine vary spatially due to system parameters (such as temperature, pressure, and pH) and geologic parameters (such as mineralogy and geochemistry). For the region associated with this study, it is most probable that many brine solutions exist due to the aforementioned reasons (geographically the region of study covers tens of thousands of square miles). If the wells in these areas develop a tendency to scale, the pipe surface areas will close, decreasing the cross-sectional area of the pipe, and possibly the annular space (especially towards the bottom of the well). This cross-sectional area loss will require greater head values to drive the system, lowering efficiency. If enough of the cross-sectional area is closed, flow may become impossible.

Two proposals are made to deal with the issue of precipitation. First, an analysis of the brine should be conducted prior to the well being converted. This analysis along with the design parameters (flow and temperature parameters) should indicate to what degree scaling may be an issue. Second, if scaling is an issue, the perforations of the lateral portion of the well can be sealed so that water cannot interact with the formation. For this case, water chemistry can be completely controlled since it will now behave as a closed-looped system.
2.3.7 Conversion Infrastructure
In order to utilize the energy from one of these wells, it must first be retrofitted with equipment that enables the energy extraction to take place. Three main components are required: an insulator pipe, a pump, and a heat conversion device or heat exchanger. An insulator pipe fabricated out of polystyrene (either hard coated or covered in a thin metal jacket) would cost approximately $25,000. A pump to run a system would cost approximately $5,000. For electric power, several companies manufacture Organic Rankine Cycle (ORC) devices that run approximately $400,000; the ORC device represents the bulk of the investment. A 1 MW well would pay for this investment in approximately 2 to 3 years by generating approximately $200,000 of revenue annually. Assuming an ORC device lifetime of 20 years and $30,000 annually for operation and maintenance costs, one retrofitted well can generate $2.89 million in profits over a 20 year period.

For wells of temperature too low for economic production of electricity, the heat may be utilized for industrial applications or residential/commercial heating. For this case, well proximity to structure is important as costs quickly escalate for any increase in distance between the well and structure using the energy. While there is no hard limit in how far the hot fluid can be piped, it will quickly become uneconomical if there is any significant distance between site and well. This case will have a much lower investment than the electric generation case since the ORC device will not be needed. In addition to the insulator pipe and pump, heat exchangers would need to be purchased and would cost tens of thousands of dollars or more depending on application.

2.4. Summary and Conclusions
This research proposes technology that can extract geothermal energy from Marcellus and Utica wells. It has been theoretically demonstrated that most of the Marcellus and Utica wells have potential for low temperature geothermal resource applications. While revenues may not be substantial for selling the heat energy (annual revenues would be approximately $5,000,000 USD if heat was sold annually from the majority of wells), the potential exists for many households or industry to capitalize off of renewable and low/no emission heat energy. The process of extracting this energy is truly an energy mining situation, as recharge rates are low. This must be taken into account for designing sites, site spacing, and lifetime.
Nomenclature for equation variables

\( A_C \) cross-sectional area of pipe \((m^2)\)
\( A_I \) cross-sectional area of pipe for downward flow \((m^2)\)
\( A_O \) cross-sectional area of pipe for upward flow \((m^2)\)
\( AM_{HT} \) Logarithmic mean area of heat transfer \((m^2)\)
\( C \) specific heat of fluid \((\text{Joules/kg}^\circ\text{C})\)
\( D_I \) inner diameter of insulator pipe \((m)\)
\( D_O \) outer diameter of insulator pipe \((m)\)
\( I_T \) insulated pipe thickness \((m)\)
\( k \) thermal conductivity \((\text{W/m}^\circ\text{C})\)
\( L \) pipe length of one interval \((m)\)
\( M \) mass of fluid per unit \(L\) length \((\text{kg})\)
\( Q_F \) fluid flowrate \((l/s)\)
\( R_I \) insulation pipe thermal resistance \((\text{W/m}^2\circ\text{C})\)
\( t \) time for fluid to travel distance \(L\) \((\text{sec})\)
\( SA_I \) inner surface area of insulator pipe \((m^2)\)
\( SA_O \) outer surface area of insulator pipe \((m^2)\)
\( T_B \) borehole temperature \((^\circ\text{C})\)
\( T_E \) ending fluid temperature of pipe interval \((^\circ\text{C})\)
\( T_I \) initial fluid temperature of pipe interval \((^\circ\text{C})\)
\( T_M \) mean fluid temperature of pipe interval \((^\circ\text{C})\)
\( T_R \) rock temperature surrounding pipe interval \((^\circ\text{C})\)
\( T_S \) surface temperature \((^\circ\text{C})\)
\( V \) average velocity of fluid in pipe \((m/s)\)
\( Z \) well depth \((m)\)
\( \rho \) density of fluid \((\text{kg/m}^3)\)
References


A TECHNO-ECONOMIC ASSESSMENT OF THE RECOVERY OF METALS FROM GEOTHERMAL BRINE

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Abstract
Geothermal power is a rapidly emerging source of renewable energy. Even though this energy source has overcome many of the obstacles that inhibited its initial development, the risks and high capital costs of power plant development currently limit its full potential. New technologies, based on research to mitigate scaling complications in geothermal power plants, are being developed to target the removal of additional mineral resources. These technologies allow for additional revenues to be generated through the sales of additional electricity and of high value mineral constituents processed from the brine. Such additional revenues can be made with relatively small capital investment, enabling geothermal power plants to be more profitable. This increase in profitability may lower risk and more favorably attract investors for new power plants. This paper reviews the science, technology, and economics of geothermal brine metal recovery and presents a method of comparative economic assessment to traditional mining.

3.1. Introduction
Geothermal power has become a popular source of renewable energy. Electric generation from geothermal resources currently represents 0.5% of the world's energy needs [1]. From 2005 to 2010, worldwide geothermal power production rose 22%, an average of 4% per year, and is expected to grow at a greater rate in the future [2]. Of the renewable energy types, geothermal power represents one of the least expensive methods of energy extraction and electrical generation [3]. Geothermal power, unlike many other renewable resources, is independent of seasonal and weather factors, enabling power to be generated continuously. Furthermore, geothermal power production environmental impacts are minor, controllable, or negligible [4]. Geothermal power production, however, is not absent from problems or risks as any technology is susceptible to these. One of the key issues that initially plagued geothermal power production was the precipitation of...
silica within the power plant pipes and equipment as pressure was reduced and temperature decreased through energy extraction. This scaling issue is currently the main factor limiting the amount of energy that can be extracted from the system [5, 6, 7]. Additionally, while studying and dealing with the precipitation issues, several metals were identified to have potential economic value if selectively removed [8, 9, 10, 11]. Numerous studies have been conducted to characterize such potential to include pilot scale studies [12, 13, 14]. As research continues and new techniques and technologies are developed for selective extraction of metals from brine, industry will become more attracted to this novel form of mining. While the research and development for this technology has grown immensely, little economic analysis has been conducted. The majority of assessment for the economics of this technology is typically a simple mass flow rate value calculation. While this simple evaluation may yield an approximate value that may be gained by selling the mined metal(s), it does not adequately provide a comparative analysis to traditional mining of these metals. As with the age old idiom “comparing apples and oranges,” this paper attempts to address this issue such that brine mining can be compared to traditional mining. This Techno-economic assessment reviews the science and technology of geothermal brine mining as well, examines the minerals and metals that may be removed from brine, and assesses the economics of geothermal brine mining. An industry case study will be analyzed, and the paper will conclude with an economic comparison of geothermal brine mining and traditional mining.

Background
The risks and capital costs for the development of geothermal power plants are extensive. Electrical generation is the predominant and often only source of revenue for geothermal power plants. Scaling of mineral constituents within the brine has been known to be a source of significant issues for geothermal power plants—particularly the silica. The range of silica solubility typically falls into the range that the geothermal brine for geothermal power exists. As water temperature increases, silica is taken into the system. Consequently, as the temperature and pressure drops, silica precipitates back out, causing silica to scale onto the pipes and power plant equipment. Furthermore, the amount of heat that can be drawn out of the brine for power production is limited by this phenomenon, limiting the lower temperature at which water can be re-injected [5, 6, 7]. By controlling and manipulating the physical and chemical parameters of the brine, metal/mineral constituents can be precipitated out [15]. Silica was the initial target due to the aforementioned
reasons. Additional metals were subsequently examined for the potential of extraction, raising the question of whether valuable metal/mineral constituents could be economically extracted for additional revenues [5, 16, 17]. Numerous investigations have been conducted in an effort to answer this question, and it appears that this technology may be feasible and profitable for select minerals and metals. Simbol Incorporated, a California based sustainable materials technology company, is developing plans to mine 15,000 metric tons of lithium annually from California geothermal brines [18]. As industry continues to develop technology for this new type of mining, it is prudent to develop economic tools to assist in minimal risk implementation of new geothermal mining operations.

Recovery of metals and minerals from geothermal brines can be viewed as a type of solution mining followed by application of hydro-metallurgical techniques for isolation and purification [16]. Wei proposed that the potential of mining minerals and metals from geothermal brines is a function of mineral concentration, value, demand, import dependency, strategic consideration, existing sources of supply, technology readiness of recovery process, and resource uncertainty [9]. The commercial viability of extracting minerals from geothermal brine is dependent on mineral concentration, mining technology implemented, recovery rates, and the quality of recovered minerals [7]. Accounting for all of these parameters would be quite cumbersome, and because brine mining technology is developing and much information related to it is proprietary in nature, it is improbable that a model using the proposed parameters would be accurate. Furthermore, each model would be reservoir dependent as characteristics and constituents are variable between regions. A best first approach would be to adapt current mining economics for geothermal mining technology.

The main purpose of silica extraction is to maximize the energy extraction of the brine. This maximization of energy extraction allows fluid temperature to reach lower temperatures before reinjection which would typically produce major scaling issues. A study at a geothermal facility in Kawerau, New Zealand indicates that approximately 10-20% additional power could be generated per unit of mass of brine for the same capital invested if the risk of silica deposition is the re-injection well is minimized [7]. Silica removal from the Kawerau facility was successfully demonstrated and showed potential for a marketable silica product as well as additional thermal
extraction benefits [6]. In another example, if a geothermal power-plant has a lower temperature limit of 130° C (due to supersaturation of silica) and is allowed to further decrease to 90° C (from controlled precipitation of silica), an additional 1 megawatt (MW) of energy can be generated from every 60 liters per second of brine flow [5]. This equates to approximately $715,000 of additional annual revenue that a geothermal power-plant could generate by introducing such technology (based on $0.10 per kilowatt per hour (kW/hr) from US Energy Information Administration website and an 80% operation time per year). This additional revenue is strictly due to additional electricity being sold and not silica.

3.2. Geothermal Brine Fluid Characteristics

Geothermal fluid composition is highly variable between geothermal reservoirs around the world. The brine is thought to be developed by dissolving components by reaction of water with cooling magmas or reactions with rocks that the geothermal reservoir flows come in contact with [13]. The source of the water in a geothermal reservoir may be meteoric, connate, a mixture of the two, may contain a magmatic component from de-volatilization of hot magma. Acidities range from a pH of 5 to 9 and salinities range from 1,000 parts per million (ppm) to over 300,000 ppm total dissolved solids (TDS). Most fluids have low oxidation states and may contain ferrous iron and reduced sulfur [16]. Metal transport and mobility within geothermal fluids are typically constrained by concentration of ligands, fluid temperature, fluid pH, and redox state of the dissolved metals. Precipitation of fluid constituents is controlled by temperature decrease/boiling, dilution, increasing pH, reaction with sulfides, and redox reactions [13]. Typically, a higher geothermal brine temperature will produce a greater chemical content [5]. The chemical constituents of geothermal brines are determined by their water source, the host rock type, the reservoir temperature, and brine flow characteristics. Brine chemistry basically reflects the physical and chemical history of its flow. This indicates that different geologic environments will favor different mineral constituents and brine chemistries. Lithium, cesium, and rubidium are typically found reservoirs located in a silica-rich volcanic host rock. Iron, zinc, and other base metals are typically found in chloride-rich fluid environments [16].

Not only is the brine composition an important aspect of potential mining, but the high volumetric flowrates contribute to the potential. The process of removing energy from geothermal brine is
similar to solution mining and oil recovery water-flooding technology, except much greater volumes flow through the system. For example, a 250 MWe power plant produces up to 175,000 cubic meters ($m^3$) of brine daily. At a concentration of only 1 milligrams per kilogram (mg/kg), approximately 150 kilograms (kg) of a metal passes through the system each day [13].

Many studies have been conducted to examine various brine compositions with each one yielding a distinctly different chemical composition. While this is intuitive, it has significant implications on selective removal of constituents; each geothermal site, (i.e. brine) must be treated independently. No technology currently exists that can selectively remove any given constituent from any given brine. Furthermore, a broad approach to outline the economics of geothermal brine mining is needed so that it can apply to the diverse range of brine systems worldwide.

3.3. Metals and Minerals of Primary Interest in Geothermal Brines
Several metals have been proposed or are alleged to have the potential of being mined from geothermal brines. Metals include lithium, zinc, magnesium, manganese, iron, copper, lead, potassium, rubidium, strontium, tungsten, palladium, cesium, barium, silver, gold, and rare earth metals [5, 7, 14, 15, 16, 19]. In addition to the metals, the mineral silica ($SiO_2$) can also be a valuable constituent since it often makes up a substantial portion of the brine, has significant potential value, and must be removed before any metals can be mined.

Silica
Silica is a common and often abundant component of geothermal brines. Most hydrothermal systems equilibrate with silica such that the silica content of the brine reflects the reservoir temperature. In general, as a hotter reservoir temperature produces a higher concentration of silica in the brine. As brine temperature is decreased due to energy extraction, the silica becomes supersaturated and precipitates out in various components of the plant or injection wells. Because the degree of precipitation is a function of temperature decrease within the brine, this temperature-precipitation issue is typically the limiting factor in determining the amount of energy that can be extracted from the brine. By removing silica from the brine, more energy can be drawn out of the system instead of being injected back into the ground [5, 6, 7]. This additional energy yields additional profits that can be gained from power generation.
In order for components of the brine to be extracted, the silica must be removed first. Silica removal by controlled methods produces multiple benefits [5, 6]. In addition to removing silica for the unwanted precipitative effects, the removal process also allows for possible additional revenue from silica sales as well as other uses of the treated brine (somewhat purified water). Lawrence Livermore National Laboratory successfully established a pilot scale process that removed silica from a Mammoth Lakes, California facility by using reverse osmosis (RO). The freshwater was then used for evaporative cooling and the brine was pumped to a reactor where silica was processed out [5, 20]. Furthermore, the potential of mining lithium, cesium, and rubidium exists from the silica reduced brine of this facility [20]. Similar studies and result were realized at the Kawerau, New Zealand facility [6].

**Metals**

Base metals are typically present in geothermal brines in trace concentrations (low micrograms per kilogram (μg/kg) range) except in hyper-saline brines, where concentrations are higher [13]. Precious metals including silver, gold, palladium, and platinum are usually resent in geothermal brines in trace concentrations (low μg/kg range). Reducing agents and adsorbents have been used to recover precious metals from geothermal brines in naturally-occurring scale deposits [13]. While these precious metals are typically present in most geothermal brines, the concentrations are typically too low to be commercially feasible. For example, McKibben, et al. showed that only 7.7 troy ounces of gold are produced through one of the Salton Sea Geothermal wells each year [8]. Metals that are currently being targeted for geothermal brine mining are typically present in concentration values of thousands to tens of thousands of ppm, although high value metals may be of much lower concentration [10, 11]. Lithium is the predominate metal currently being studied for geothermal mining in the US due to its relatively high concentration, the fact that the U.S. depends on imports for this metal, and its potential for demand growth [21]. Rare earths are proposed by many authors, but no true feasibility studies have been developed.

### 3.4. Methods of Metal Recovery from Geothermal Brines

Recovery of metals and minerals from geothermal brines can be viewed as a type of solution mining followed by application of hydro-metallurgical techniques for isolation and purification
There are two basic types of recovery for constituents of geothermal brines: physiochemical methods and biological methods. Physiochemical methods include chemical precipitation, chemical coagulation, ion exchange, membrane technologies, electrochemical technologies, and adsorption using activated carbon. Biological methods include biosorption and bioaccumulation.

Physiochemical methods of extraction are widely used to extract metals from inorganic solutions, making it the primary method to adapt for the removal of metals from geothermal brine. Many physiochemical processes have been proposed, developed, and even patented for metal extraction from geothermal brine. Most physiochemical processes consist of a series of steps in which the physical aspects of the brine such as pH and temperature are controlled and chemicals are added in to selectively target desired constituents. Constituents are removed by a process such as filtration, precipitation, or electrowinning. While these methods are simple, easy to operate, and effective, they have three major weaknesses. First, they are ineffective when the mineral concentration is very low. Second, a large amount of sludge slurry will be produced during the recovery process, potentially causing higher operational costs and environmental concerns. Third, some physiochemical methods are expensive. These expenses can result from high capital costs or short lifetime of process components/materials (such as activated carbon for adsorption). Other potential issues include incomplete metal adsorption and high reagent or energy requirements.

These issues and associated costs will ultimately depend on the process that is developed, the brine composition, and to a lesser degree the regulatory constraints. There are two basic concerns associated with extracting metals and minerals from geothermal brines: the chemical reaction that causes precipitation and crystal growth of the desired product phases and the efficient removal of the precipitated particles from the brine. While much of the energy required for driving the chemical reactions for precipitation and crystal growth is typically already present in the brine, it is proposed by Patterson that any additional energy required for such reactions be generated through ultrasonic energy since well controlled, large amounts of energy can be generated in this type of hostile processing environment. Different mineral phases could be formed by selective seeding under controlled conditions. Removal of phases will take advantage of seed characteristics such as magnetism and density.
Premuzie, et al. propose a biochemical treatment for geothermal sludge that not only enables brine disposal that meets regulatory constraints, but also has potential of generating revenue by removing commercially desired metals such as gold [22]. Lo et al. present methods and reasons for recovering metals from geothermal brine by biosorption and bioaccumulation [19]. Bioaccumulation methods utilize biosorbents typically composed of a biomass of living organisms that accumulate targeted metals inside or outside the cell using an energy ATP-driven process. Biosorption is proposed as the preferred biological method since it has the advantages of easy handling and maintenance, high metal uptake capacity and treatment rate, high selectivity, low need for technical support, minimal sludge production, and high capabilities with regard to regeneration and reusability [19]. While the general concepts of proposed biochemical treatments are shown by Lo, et al., specific details such as accumulation rates, methods of extraction from the bioaccumulants, costs associated with capital, operational, and other associated expenses are not discussed. In order to appropriately compare the types of extraction (biological vs. physiochemical), rates of extraction, capital costs, and operating costs need to be developed and compared, thus requiring future research.

Figure 25 shows schematics of a general physiochemical process and the biological methods for metal recovery. The left side shows a flowsheet from patent 8,518,232 describing selective recovery of manganese, lead, and zinc from geothermal brine [23]. This particular patent is held by Simbol Incorporated—the same company mentioned previously. This flowsheet is just one example of the many proposed processes for selective recovery of metals from geothermal brines. The right side of Figure 25 shows the biological methods of recovery. Metals attach to the surface in biosorption, whereas cells ingest metals in bioaccumulation. Physiochemical methods are currently being used for extraction in pilot scale studies; biochemical methods are currently only in the research phase.

3.5. The Economics of Extracting Metals from Geothermal Brine

The commercial viability of extracting minerals from geothermal brine is dependent on mineral concentration, mining technology implemented, recovery rates, and the quality of recovered minerals [7]. Wei showed the potential of mining minerals and metals from geothermal brines as a function of mineral concentration, value, demand, import dependency, strategic consideration, existing sources of supply, technology readiness of recovery process, and resource uncertainty [9].

Silica

As previously stated, the main purpose of silica extraction is to maximize the energy extraction of the brine. In addition to the profits realized from additional electricity sales, additional profits can be generated from selling the silica that is removed from the brine. Silica is used worldwide in a variety of applications to include ceramics, chemicals, filtration, specialty glass, paints, electronics and other technologies according to the USGS [24]. Most high quality silica material is produced by dissolving quartz sand in an alkali solution and precipitating colloidal silica by acidification [16]. The average growth of specialty silica in the United States is approximately 4% per year. The daily consumption of commercial grade silica was approximately 6 million pounds in 2005. The 2003 world market was 190,000 tons per year for precipitated silica and 68,000 tons/year for colloidal silica with a 4% annual increase in demand [5]. The price of silica varies widely and is
based on its purity and physical characteristics. In 2000, specialty silica prices ranged from $35 per ton to over $84 per ton, and producer prices that were reported to the USGS for high grade specialty silica ranged from up to several hundred dollars a ton to over $1,000 per ton [24]. The potential revenue stream for a 50 MWₑ power plant in the Salton Sea geothermal field has the potential of producing $10.2 million per year from silica sales based on a 60% silica recovery rate, a selling rate of $2,200 per metric ton, and a plant capacity factor of 95% [25].

**Metals**

A patented zinc extraction technology from geothermal brine was developed by The Minerals Laboratory of BHP Minerals. Geothermal brine is mixed with an immiscible anionic organic solvent selective to the extraction of zinc chloride. The zinc chloride-loaded anionic extractant is then stripped with water to produce an impure zinc chloride solution and then mixed with a cationic solvent, selective for zinc. Zinc is stripped from the loaded cationic extractant by sulfuric acid and recovered as special high grade (SHG) zinc metal by conventional electrowinning [14]. Table 9 compares the costs (1993 costs) from extracting zinc from geothermal brine to traditional mined zinc [14]. Total cost for mining and processing zinc is approximately 55¢ per pound cheaper using geothermal mining methods as compared to traditional mining methods. This, similarly to Patterson’s findings, appears to be due to mining, crushing, and milling costs absent from the geothermal mining process.

<table>
<thead>
<tr>
<th>Item</th>
<th>Unit</th>
<th>Primary Zinc</th>
<th>Geothermal Zinc</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capital Cost</td>
<td>US¢ per pound Zn</td>
<td>100</td>
<td>80</td>
</tr>
<tr>
<td>Raw Material Cost</td>
<td>US¢ per pound Zn</td>
<td>35-40</td>
<td>0</td>
</tr>
<tr>
<td>Operating Costs</td>
<td>US¢ per pound Zn</td>
<td>15-20</td>
<td>25-30</td>
</tr>
<tr>
<td>Total</td>
<td>US¢ per pound Zn</td>
<td>150-160</td>
<td>105-110</td>
</tr>
</tbody>
</table>

Figure 26 illustrates the comparison of energy used in mineral extraction between geothermal brine mining and conventional mineral mining. Approximately 70% of the total energy spent for crushing, grinding, and digestion in traditional mining is not required in the geothermal brine
mining. This translates to a 70% reduction in the energy costs associated with mining and mineral processing for minerals that can be extracted from brines.

**Figure 26.** Illustration showing the energy use in conventional mineral extraction from conventional mines with that of mineral extraction from geothermal brines. [Schematic]. Adapted from Patterson, Mark. “Geothermal Brines-High Value Mineral Extraction.” GRC Transactions, Vol. 30 (2006), 589-584.

Economic comparison should focus on this lack of costs for geothermal brine mining, geothermal brine mining technology gaps, and the difference in grade/concentration of desired constituents. This is a source of new research as no papers address this or take this approach.

**Simbol Materials—An Industry Case Study**

To assess the state of this technology within industry, a case study of the industry’s leading player is presented. Simbol Incorporated is a sustainable minerals technology company working on geothermal brine mining endeavors. In 2008, Simbol Inc. formed and licensed technology developed by the Lawrence Livermore National Laboratory. In 2010, Simbol received $3 million from DOE for a $9.3 million project to produce lithium, manganese, and zinc from California’s...
Salton Sea geothermal reservoir. In 2013, Simbol successfully demonstrated production of high-purity lithium hydroxide through an electrolysis method and produced the world’s first battery-grade lithium carbonate from geothermal brine. Over 9,000 hours of plant operation has been successfully demonstrated, and full-scale production is anticipated in 2018 [26].

Figure 27 shows a schematic of the process that Simbol uses for its metal extraction from brine. Brine enters the system; energy from the brine drives a turbine and brine is processed for separation. Steam and carbon dioxide are used in the separation process, rather than released to the atmosphere or re-injected into the reservoir. Purified water is used for cooling. Residual brine is re-injected into the reservoir; the output is lithium, manganese, and zinc.

Figure 27. Illustration showing the Simbol Inc. process to remove metals from geothermal brine. [Image]. Adapted from http://www.simbolmaterials.com/.

Simbol uses a unique reverse-osmosis process, but details are not public since the process is proprietary. Some of the key process details that are rather significant are that virtually zero waste is produced, emissions are consumed through the process, traditional invasive mining is
eliminated, annual production will provide enough lithium for 1.6 million plug-in hybrid electric vehicles, and up to 11 facilities are anticipated with a productive estimated life of 600 years.

While the future outlook appears to be promising, technology still lags for a full transition from traditional mining to brine mining. Further research must be conducted to show the NPV (Net Present Value) differences between the traditional and geothermal brine mining methods. One approach may be to treat geothermal brine mining similarly to traditional mining by assigning a cut-off concentration (similar to a cut-off grade) to constituents targeted for mining. Cut-off concentration with associated NPVs will provide two functions. First, this will assist industry in determining what metals are economical to mine with already established technologies. Second, this will provide value targets that technology must achieve in order for a targeted metal to be economically extracted from a brine of a certain concentration. As metal resources become scarcer and prices climb, these technologies will become more economical. This approach will provide a method to measure when, or at what price the technology shift can occur.

3.6. Comparison of Traditional and Geothermal Brine Mining
This section attempts to compare and contrast the basic similarities and differences between traditional mining and geothermal brine mining, concluding with a mathematical model. Table 10 shows the general cost types associated with traditional mining methods. Cost types may be broken down various ways, but most analyses follow a breakdown structure similar to Table 10.

<table>
<thead>
<tr>
<th>Cost Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capital</td>
<td>Typically not factored into economics until NPV calculation</td>
</tr>
<tr>
<td>Overhead</td>
<td>Can be averaged out over the material grade types</td>
</tr>
<tr>
<td>Mining</td>
<td>Costs from extraction to the milling plant</td>
</tr>
<tr>
<td>Milling/Processing</td>
<td>Costs from milling plant to refining</td>
</tr>
<tr>
<td>Mining/Milling Waste</td>
<td>Costs related to disposal requirements/standards</td>
</tr>
<tr>
<td>Refining/Sales</td>
<td>Post-processing costs; may be combined or separated</td>
</tr>
</tbody>
</table>
Capital costs, the major expense in traditional mining operations, are not typically accounted for in mine planning costs until NPV evaluation. Mining, milling, and refining/sales costs are used to establish the ultimate pit cutoff grade (ore targeted for extraction). Milling and refining/sales costs are used to establish the milling cutoff grade (ore sent to the mill). Overhead and mining/milling waste costs are typically included in the mining and milling/processing costs but may be separated to provide detailed accounting for operations [27, 28]. Table 11 shows general mining costs compared between traditional and geothermal brine mining.

### Table 11. General cost comparison of traditional mining and geothermal brine mining.

<table>
<thead>
<tr>
<th>Cost Type</th>
<th>Traditional Mining</th>
<th>Geothermal Brine Mining</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capital</td>
<td>Very High</td>
<td>Low</td>
</tr>
<tr>
<td>Overhead</td>
<td>Moderate</td>
<td>Moderate</td>
</tr>
<tr>
<td>Mining</td>
<td>High</td>
<td>None</td>
</tr>
<tr>
<td>Processing</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Refining</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td>Sales</td>
<td>Very Low</td>
<td>Very Low</td>
</tr>
</tbody>
</table>

Capital costs in geothermal brine mining are very low to the high capital costs of traditional mining since most costs were accounted for with the geothermal power plant costs. Minimal capital costs will be needed for constituent extraction. These costs will be similar to those of a milling/processing plant and most likely a fraction of the cost since no crushing or grinding will be required. Mining costs comprise a significant portion of the costs for traditional mining; these costs are nonexistent for geothermal brine mining. Processing costs will be similar for both mining types, but will most likely be lower for the geothermal brine mining since no grinding and crushing is required. Overhead, refining, and sales costs will be very similar for both types of mining.

In traditional mining, costs are typically defined in such a way as to determine a cutoff value. All material that is extracted can be categorized according to types shown in Figure 28. The material category determines the actions to be taken for a given material.
Figure 28. Illustration showing material types extracted during traditional mining operations.

Overburden and ore of grade less than the cutoff grade is discarded as waste; this includes both the waste and the unrecovered metal from the ore that is below the cutoff grade. All material above the cutoff grade is sent to the milling plant for processing. Waste material along with unrecovered metal after processing will be discarded as waste. Recovered metal will be refined and sold. Figure 29 combines Table 11 and Figure 28, showing costs associated with the various material types for traditional mining methods. Mining and overhead costs are applied to all material types. Milling costs are associated with all ore that has a grade greater than the cutoff value. Refining/sales costs apply only to the recovered metal. Mining waste costs, if used, apply to waste material and unrecovered metal from ore with grade greater than the cutoff value. Profits apply only to recovered metal.
<table>
<thead>
<tr>
<th>Mining Costs</th>
<th>Mining Waste Costs</th>
<th>Milling Costs</th>
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</table>

**Figure 29.** Illustration combining material types extracted during traditional mining operations with associated costs.

**Figure 30.** Illustration showing material types extracted during geothermal brine mining operations.
Figure 30 illustrates the basic types of material extracted during geothermal brine mining operations. Note that regions C through F are absent in geothermal brine mining operations. Region B is most closely related to waste material from processing of traditional mining. Region A is very similar for both types, except geothermal brine mining is now related to a cutoff concentration.

Figure 31 shows the basic material types associated with geothermal brine mining combined with their associated costs. Comparison of Figure 29 with Figure 31 show the potential cost savings associated with geothermal brine mining. The extraction of metal associated with geothermal brine mining occurs in two stages: processing, extraction, and disposal of material required for desired constituent extraction, and the extraction of desired constituents. Almost all costs associated with these stages are dependent with the technology and energy costs for constituent removal. Of these costs, the technology cost is the most variable, since the cost of extraction should decrease as extraction technology evolves. Higher technology costs will be economical as traditional reserves are depleted.

**Figure 31.** Illustration combining material types extracted during geothermal brine mining operations with associated costs.
3.7. Equations
This section attempts to establish a method for determining cutoff concentration. This value is
developed in a manner similar to the cutoff grade for traditional mining methods.

3.7.1. Equations for traditional mining
The cutoff grades for traditional mining methods will be developed first so that the geothermal
brine mining concentration cutoff can be developed from this basis. The profit or loss in in mining
one metric ton of ore of grade $x$ by traditional methods is given by:

$$U_{ore}(x) = x \times r(V - R) - (M_o + P_o + O_o)$$  \hspace{1cm} (1)$$

where
$x$ = average grade (oz/st)
$r$ = recovery of valuable product (%)
$V$ = value of one unit of valuable product ($/oz$)
$R$ = refining, transportation, sales, and other costs per unit of valuable product ($/oz$)
$M_o$ = mining cost per metric ton of ore processed ($/st$)
$P_o$ = processing cost per metric ton of ore processed ($/st$)
$O_o$ = overhead cost per metric ton of ore processed ($/st$)

The value lost for removing one metric ton of material less than grade $x$ (waste) is given by:

$$U_{waste}(x) = -(M_w + P_w + O_w)$$  \hspace{1cm} (2)$$

where
$M_w$ = mining cost per metric ton of waste processed ($/st$)
$P_w$ = processing cost per metric ton of waste processed ($/st$)
$O_w$ = overhead cost per metric ton of waste processed ($/st$)

By setting equations (1) and (2) equal and solving for $x$, the ultimate cut-off grade is calculated
and given by:
\[ x_c = \frac{(M_o + P_o + O_o) - (M_w + P_w + O_w)}{r(V - R)} \]  \hspace{1cm} (3)

By ignoring the mining and waste costs associated with equation (3), the mill cut-off grade is calculated and given by:

\[ x_c = \frac{P_o + O_o}{r(V - R)} \]  \hspace{1cm} (4)

The profit for traditional mining is given by:

\[ P_t = (V - s) \times Q_r - (Q_c \times (P_o + O_o)) - (Q_m \times (M_o + M_w)) - (Q_w \times ((P_w + O_w)) \]  \hspace{1cm} (5)

where

- \( Q_r = \) recovered ounces of targeted material (oz/yr)
- \( Q_c = \) tons processed by mill (st/yr)
- \( Q_m = \) total material mined (st/yr)
- \( Q_w = \) milling waste processed (st/yr)

### 3.7.2. Equations for geothermal brine mining

The equations that govern geothermal brine mining are similar to those given for traditional mining with a few adjustments or exclusions. The profit or loss in mining one metric ton of ore of concentration \( x \) from brine is given by:

\[ U_{ore}(x) = c \times r(V - R) - (P_b + O_b) \]  \hspace{1cm} (6)

where

- \( c = \) average concentration (oz of metal/st of water)
- \( P_b = \) cost per metric ton of ore extracted by geothermal mining ($/st)
- \( O_b = \) overhead cost per metric ton of ore extracted from brine ($/st)
Note that average concentration units can be converted to ppm by using the mass of targeted constituent and water. In these calculations, c will be in units of ounces of metal per short tons of water.

The value lost for treating brine waste is given by:

\[ U_{\text{waste}}(x) = -(L_b) \]  

(7)

where

\[ L_b = \text{cost of brine treated per metric ton of ore processed (disposal compliance)} \ (\$/\text{st}) \]

By setting equations (6) and (7) equal and solving for x, the ultimate cut-off concentration is calculated and given by:

\[ x_c = \frac{P_b + O_b - L_b}{r(V - R)} \]  

(8)

The profit for geothermal mining is given by:

\[ P_g = (V - s) \times Q_r - (Q_b \times (O_b + L_b + P_b)) \]  

(9)

Equations (4) and (8) are similar in interpretation, as both are related to cutoff value. However, they cannot be compared from a strict economic perspective since the cost basis is very different for the two types (as shown in Figure 4 through Figure 7). Equations (5) and (9) should form the basis of determining NPVs for each mining type. Once an NPV is developed for each type, they can be compared in the same manner. This method can be used to determine what concentration values are required in geothermal brine for selective removal to be economical (given a technology cost and constituent value). A given constituent concentration and technology combination cost must be more profitable than the extraction of the same material by traditional mining methods if it is to be profitable. This same procedure can be used to target the cost that technology must reach, or vice versa, the price the constituent must reach for a given technology cost, for geothermal brine mining to be economical for a given constituent. As traditional reserves are depleted, this method
will show when transition from traditional mining to geothermal brine mining should occur. These techniques can also be applied to brine mining from oil and gas wells, solution ocean mining, and in-situ leaching mining methods as these technologies are potentially developed.

3.8. Conclusion
This chapter examined the techno-economics of the recovery of metals from geothermal brines. A method of comparing costs and NPVs of traditional mining and geothermal brine mining has been developed so that decisions can be made in determining whether constituents are economical to mine from geothermal brines. Geothermal brine mining shows significant potential and may develop into a mainstream mining source as traditional reserves diminish.
Nomenclature for equation variables

c  concentration of metal in brine (oz/st of water)

P_b  cost per metric ton of ore extracted by geothermal mining ($/st)

O_b  overhead cost per metric ton of ore extracted from brine ($/st)

L_b  cost per metric ton of brine treated before disposal ($/st)

M_o  mining cost per metric ton of ore processed ($/st)

M_w  mining cost per metric ton of waste processed ($/st)

O_o  overhead cost per metric ton of ore processed ($/st)

O_w  overhead cost per metric ton of waste processed ($/st)

P_o  processing cost per metric ton of ore processed ($/st)

P_w  processing cost per metric ton of waste processed ($/st)

P_{tg}  annual profits for traditional or brine mining ($)

Q_b  tons processed by brine extraction process (st/yr)

Q_c  tons processed by mill (st/yr)

Q_m  total material mined (st/yr)

Q_r  recovered ounces (oz/yr)

Q_w  milling waste processed (st/yr)

R  refining, transportation, sales costs, and other costs per unit of valuable product ($/oz)

r  recovery (%)  
s  sales cost ($/oz)

V  value of one unit of valuable product ($/oz)

x  average grade (oz/st)
References


A DYNAMIC SUPPLY-ECONOMIC MODEL FOR MINERAL EXTRACTION FROM GEOTHERMAL BRINE

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Abstract
This chapter was initially developed as a proposal to the Department of Energy in response to a grant for geothermal energy research. Unfortunately the grant was not obtained. The proposal addressed the need for a dynamic supply-economic model for extracting minerals from brines (initial focus was geothermal brines, but the same concepts can be applied to oil and gas brines) as well as the usefulness of an interactive database containing mineral constituent concentrations in brines. This chapter summarizes the chief concepts of the proposal as these ideas build on the previous chapters of this thesis. It is the desire of the author that a future researcher fully develop these concepts into reality.

4.1. Research Overview
4.1.1. Background
As previously shown, industry has already demonstrated the potential of processing minerals from geothermal brines [1]. Many parameters, such as resource supply and demand, resource availability, technology development economics, and environmental constraints contribute to a venture’s chance of success. As projected shortfalls of resources potentially available in geothermal brines rise, indicated parameters may shift, allowing industry to successfully design and/or implement new extraction technologies. In an attempt to offset risk and promote confidence in new technology development, a supply-economic model should be developed to fully engage industry to take on such ventures. Chapter three formed the basis for the development of such a model.

Life Cycle Analysis and constraint theory [2, 3, 4] should be used to optimize the supply-economic model by using parameters associated with the extraction of minerals from geothermal brines. The
model would focus on the economic constraints required for developing new technologies for the extraction of minerals from geothermal brines. For example, this model would show minimum mineral concentrations in brines required to offset development and processing costs. The same model would also be used to show when a new process should be implemented based on supply and demand changes or a new technology development with lower operational costs. Thus, this model can continually be used by industry to target certain minerals or certain processing technologies as conditions ripen. In addition to the model development, a database should be created that will provide mineral concentrations of various brines of geothermal power plants as well as oil and gas brines in the United States and worldwide. The aim of this database would be to demonstrate and evaluate concentration variances of geothermal brines of power plants as well as oil and gas brines and will further serve as a comparison of any concentration changes over time for a particular geothermal location. This information would be available for the general study and continued development of geothermal brine science as well as ancillary information to a fully developed supply-economic model for industry’s use in risk assessment and technology development.

4.1.2. Research Goal
Two distinct goals would be sought through this project. The first and primary goal would be the formulation of a supply-economic model for the extraction of minerals from geothermal brines. Critical success factors for this objective would include identifying constraints that currently prohibit potential metals from being mined while also identifying current rates of production and consumption as functions of cost. The second goal would be to establish a database that shows mineral concentration values of various brines of geothermal power plants as well as oil and gas brines. The project will initially aim at characterizing brines within the United States and then encompass regions worldwide as more research is conducted. Having one place to access concentration information is essential for efficient evaluation of sites as well as for general research.

4.1.3. Department of Energy Impact
Department of Energy (DOE) funding was initially sought after for this project. While this funding was not awarded due to unfortunate complications, this entity would be the ideal route for funding
and promoting this type of research. The DOE often funds research of this type and furthermore has the ability to promote results to a much broader audience than any single university or research organization.

4.2. Technical Description, Innovation, and Impact
4.2.1. Relevance and Outcomes
This project will produce a supply-economic model for the extraction of minerals from geothermal brines as well as a database for geothermal brine concentrations of geothermal power plants in the US. These two deliverables are in complete alignment with the goals of the DOE as they will potentially mitigate current barriers to the development of strategic material extraction from geothermal brines. These barriers will be mitigated by making known the indeterminate economic feasibility factors for profitably extracting metals from geothermal brines (first deliverable and goal) and by providing information to the current lack of knowledge of the extent and location of the available resource (second deliverable and goal). Additionally, the database will target assessment of current rare earth and near-critical metals for potential extraction volumes and rates. Targeted high demand resources will include lithium, manganese, tellurium, and zinc. Targeted critical rare earth elements (REEs) will include dysprosium, terbium, europium, neodymium, and yttrium (Table 12).

Table 12. Critical Elements.

<table>
<thead>
<tr>
<th>Critical Elements to be Examined</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>High Demand Resources:</strong></td>
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<tr>
<td>Lithium</td>
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<tr>
<td>Manganese</td>
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<tr>
<td>Tellurium</td>
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</tr>
<tr>
<td>Zinc</td>
<td></td>
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<tr>
<td><strong>Critical REEs:</strong></td>
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<tr>
<td>Dysprosium</td>
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<tr>
<td>Terbium</td>
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<td>Europium</td>
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</tr>
<tr>
<td>Neodymium</td>
<td></td>
</tr>
<tr>
<td>Yttrium</td>
<td></td>
</tr>
</tbody>
</table>

Published literature should be reviewed in an effort to maximize model capabilities. The database would be established using Google Fusion Tables. Initial values would be populated by using
concentrations from already published literature. Geothermal power plant companies would be contacted and shown the capabilities of this database. For oil and gas brines, production companies would need to be contacted for possible data collection of regions that data is not available. A team should be tasked to obtain 50 milliliter (mL) brine samples from sites in order to perform analysis of the targeted high demand resources and REE (Table 11). Inductively coupled plasma atomic emission spectroscopy (ICP-AES) and inductively coupled plasma mass spectrometry (ICP-MS) will be used to determine concentrations using standard methods and procedures. These two procedures are routinely performed at most universities. Filter kits are available for purchase to mitigate issues associated with the salts. Detected concentrations would then be added to the database. Significant concentrations or trends will be further researched and published. A sample list of geothermal power plants is shown in Appendix A. This list shows the major geothermal power plants in the United States that could be sampled for the database. Oil and gas fields would be slightly more complex since many different producers often utilize overlapping regions, but the same general concept can be applied to gathering samples from them.

The Google Fusion Tables approach enables geothermal power plant locations to be mapped and then correlated with large datasets [5]. Datasets would include concentrations of minerals and metals of interest. These datasets would also allow for concentrations with marked time values to be added so that it will be possible to observe concentration changes with time for a particular site. An example of a dynamic database along with a figure representing various sites (in this case Rare Earths Deposits) within the US is shown in Figure 32. A life dynamic map with filtering capabilities can be found on the following website: www.google.com/fusiontables/DataSource?snapid=S2321659VJN. Once the table is displayed in the web browser go to the ‘Visualize’ menu and select ‘Map’.
There are two expected outcomes. The first expected outcome is the development and use of an accurate supply-economic model for the extraction of minerals from geothermal brines. It is further expected that industry would use this model to assist in successful future ventures of brine mining. The second expected outcome is the development, use, and continued growth of a database of geothermal brine concentration values of geothermal power plants and oil and gas brines in the US. It is further expected that this information would be used for general scientific and geological research. It should be noted that some industry entities may choose to use this database and keep findings private. In this case industry would still benefit from this database. While the second outcome will be limited in the short-term, it should help drive innovation and technological improvements in this area.

4.2.2 Innovation and Impacts

No supply-economic models are known to exist for the extraction of metals from geothermal brine. A model of this type would greatly assist industry in further technology development for the
extraction of metals from geothermal brine by increasing confidence and minimizing risk for such ventures. No known large-scale database of concentrations for geothermal brines or oil and gas brings is known to exist. A database of this type would provide industry with constraints for extraction evaluation. Furthermore, this database would enable new research to be conducted in the disciplines of geology and geothermal science.

4.3. Project Summary

4.3.1 Project Objective

The primary objective of this project would be to provide tools to industry that mitigate risk, promote confidence, and assist in successful operations of mineral extraction from geothermal brines. This primary objective would be met through the previously mentioned two main deliverables: the formulation of a supply-economic model for the extraction of minerals from brines and the establishment of a database that can be used to show mineral concentrations of various brines. Expected outcomes will be the successful completion of the project objective and goals as well as usage of the model and database by industry.

4.3.2 Technical Summary

This project would provide a supply-economic model to assist in minimizing risk in the technological development of mineral extraction from geothermal brines as well as a database for mineral concentrations of geothermal brines located in the United States. The database would be generated with Google Fusion Tables. Two major objectives would encompass this project. The first major objective would be the formulation of a supply-economic model that will assist industry with minimizing risks for technological developments of mineral extraction from geothermal brines. The second major objective would be the production of a database for mineral concentrations in geothermal brines. Although both objectives would be performed simultaneously through much of this project, the formulation of the supply-economic model is placed as the first (primary) objective because of its near-term significance to industry; the model can be used for risk mitigation for any brine mining venture. Industry input would be gathered and considered for model refinement during site visits. The development of a database for mineral concentrations in geothermal brines, while expected to be completed before the primary objective, is placed as the second objective. This database is an ancillary product to the model. It must be
emphasized that this database is significant as it will allow industry to identify potential minable resources, and the database will also be a wealth of consolidated information for scientists, researchers, engineers, and industry. This information would potentially be used for future studies and developments in science and technology. This dynamic database would allow information input by industry. Industry entities will be able to keep data private or enable it for public view. Growth of this database will allow potential regional models to be built and local concentration changes to be realized.

4.4. Summary
In summary, a project for the formulation of a dynamic supply-economic model for brine mining as well as an interactive database is promoted as an idea for a future project. While this project was not realized during the author’s graduate school endeavor, it is hoped that this work may serve as a basis for a future project or Master’s thesis.
References


CHAPTER FIVE
THESIS SUMMARY

Oil and gas production technology has steadily evolved over the past 150 years. As commodities, oil and gas play important roles in both the US and worldwide markets as it is often viewed as a critical economic driver and assessment tool of the marketplace. The market, being dynamic, can quickly create constraints for new ventures and are often difficult to predict. Any additional revenue that can be made from an oil or gas well will help mitigate risks associated with development and investment. Developing technologies to build on already available infrastructures will also potentially mitigate substantial investment costs for subsidiary technologies as well as ancillary environmental issues. This thesis examined the feasibility of retrofitting Marcellus and Utica gas wells into geothermal wells and the potential of utilizing oil and gas wells as sources of traditionally mined materials.

5.1. Geothermal Energy from Oil and Gas Wells
Chapter two presented an assessment of geothermal energy extraction from gas wells in the Marcellus and Utica Shale plays. A total of 9,289 wells in the Marcellus and Utica Shale plays were analyzed for their geothermal potential. Well position data for Marcellus and Utica Shale wells were obtained from a Pennsylvania Department of Environmental Protection (PADEP) public database [1]. For each well location, the depth was estimated as the addition of the median depth to formation and median thickness of the shale formation. Marcellus and Utica Shale geospatial data was provided by the Marcellus Center for Outreach & Research (MCOR) [2]. Borehole temperature values were then assigned to each well identification number by running well depth values through a thermal model developed by Cornell University for the Appalachian Basin. Surface temperature, borehole temperature, and well depth values along with some assumed inputs were then used to calculate thermal potential of each well.

Results show that these wells can be used in limited scope for energy extraction and in limited cases for electrical generation.
5.2. Metal and Mineral Mining from Oil and Gas Wells
Chapters three presented a techno-economic assessment of the recovery of metals from geothermal brines. A method of comparing costs and Net Present Values (NPVs) of traditional mining and geothermal brine mining was developed so that decisions can be made in determining whether constituents are economical to mine from geothermal brines. Geothermal brine mining shows significant potential and may develop into a mainstream mining source as traditional reserves diminish. Chapter four outlined a study with chapter three serving as the basis with the hopes of future research being conducted as proposed.

5.3. Summary
In summary, this thesis proposes concepts that can assist the oil and gas industry with the recovery of additional assets (energy and metals) from existing infrastructure. These additional assets can potentially offset some of the risks associated with oil and gas development. Additionally, additional profits may be generated from the recovery of these assets.
References


## APPENDIX

### Geothermal Powerplants in the United States

<table>
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<th>Powerplant Name</th>
<th>State</th>
<th>City</th>
<th>Type</th>
<th>Location</th>
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