Assessment of New Approaches in Geothermal Exploration Decision Making

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ABSTRACT

Geothermal exploration projects have a significant amount of risk associated with uncertainties encountered in the discovery of the geothermal resource. Two of the largest challenges for increased geothermal deployment are 1) understanding when and how to proceed in an exploration program, and 2) when to walk away from a site. Current methodologies for exploration decision-making are formulated by subjective expert opinion which can be incorrectly biased by expertise (e.g. geochemistry, geophysics), geographic location of focus, and the assumed conceptual model. The aim of this project is to develop a methodology for more objective geothermal exploration decision making at a given location, including go/no-go decision points to help developers and investors decide when to give up on a location. In this scope, two different approaches are investigated: 1) value of information analysis (VOIA) which is used for evaluating and quantifying the value of a data before they are purchased, and 2) enthalpy-based exploration targeting based on reservoir size, temperature gradient estimates, and internal rate of return (IRR). The first approach, VOIA, aims to identify the value of a particular data when making decisions with an uncertain outcome. This approach targets the pre-drilling phase of exploration. These estimated VOIs are highly affected by the size of the project and still have a high degree of subjectivity in assignment of probabilities. The second approach, exploration targeting, is focused on decision making during the drilling phase. It starts with a basic geothermal project definition that includes target and minimum required production capacity and initial budgeting for exploration phases. Then, it uses average temperature gradient, reservoir temperature estimates, and production capacity to define targets and go/no-go limits. The decision analysis in this approach is based on achieving a minimum IRR at each phase of the project. This second approach was determined to be less subjective, since numerical inputs come from the collected data. And it helps to facilitate communication between project managers and exploration geologists in making objective go/no-go decisions throughout the different project phases.

1. INTRODUCTION

Exploration of any natural resource has a certain amount of uncertainty and risk (Kacewicz, 2004). Geothermal exploration risk has been defined as follows: not achieving an economically acceptable production capacity with minimum flow rates and reservoir temperatures (Schulz et al., 2007). While drilling a well at a certain location, a decision-maker is choosing to take that risk with an estimated probability of achieving the acceptable production capacity. A decision-maker's goal is to logically determine where and when to drill the production well by analyzing data collected at a site.

1.1 Geothermal Exploration Overview

Figure-1 shows a typical exploration program with typical field activities and the decision options typically considered for each step in the process. In each phase of exploration, a certain portion of the activities is synthesizes the stratigraphic, structural, hydrologic and thermal data. At the end of each phase conceptual models and volumetric assessments of the reservoir are updated to target the production wells and total production capacity of the geothermal reservoir. A decision is then made to conduct additional exploration activities, drill the first production well, or leave the field.

An exploration program typically starts with gathering from literature, existing offset wells and other surface manifestations and then continues with applying of various geological, geochemical, and geophysical surveys following successive phases (IGA, IFC, 2013). Different exploration programs can be designed with appropriate exploration techniques for different geothermal play types. It is important to know that no single exploration technique provides the key to a successful conceptual model and a successful discovery at all locations. Conceptual models are typically developed at each stage of exploration as a representation of the current best understanding of a geothermal system. A conceptual model is a set of information that best illustrates geology, geochemistry, and reservoir fluid and rock properties of a geothermal system (Cumming, 2009). At early exploration stages, the conceptual model can be as simple as geological cross-sections correlated with maps of conceptual elements like temperature and some other illustrative data sets. At later exploration stages, it can be built-up as complex three-dimensional (3D) subsurface models including 3D geophysical data (e.g. magnetotelluric, resistivity) and 3D temperature distribution from temperature data (Akar et al., 2011). Reservoir performance can be considered by parameters such as, temperature, pressure, permeability, porosity and water chemistry. Even without wells, isotherms can be drawn using geothermometry from surface manifestations, boiling point considerations and characterizations of permeability using resistivity and other methods (Cumming, 2009). This information may support the location and the design of temperature gradient wells or slim-hole wells. During exploration phases, it has been recommended that more than; one conceptual model could be developed using the available information, and updated with additional data in each phase (Boseley et al., 2010). Any additional data provides new constraints for determining the exact geometry of the reservoir and its controlling structures.

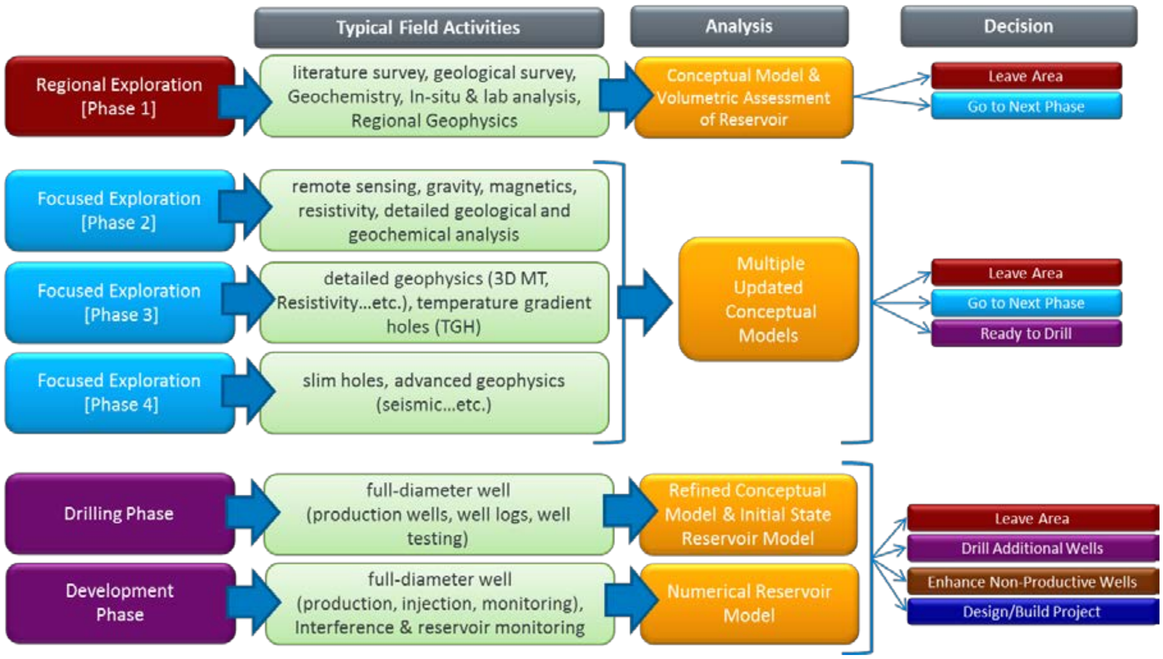

Figure 1: A Typical geothermal exploration program having different phases, with typical field activities, analyses and the decision options.

1.2 Subjectivity in Exploration

In exploration decision making there is subjectivity and uncertainty. We typically talk about uncertainty in terms of quality of data – how uncertain are the data based on the type of technique employed and the quality of the information? Subjectivity refers to how someone's judgment is shaped by personal opinions and feelings instead of outside influences. Subjectivity negatively affects reproducibility. Two experts could reproduce the same estimate (e.g., for temperature) with the same level of uncertainty. Both uncertainty and subjectivity contribute to project risk. We investigate methods that could be employed to reduce subjectivity and increase reproducibility**.**

Prior to drilling, the character and structure of the subsurface cannot be directly observed, but the exploration techniques described above have been developed to help get a sense of what the subsurface might look like prior to drilling. Interpretation of these data requires reliance on previous experience and analogs, but is highly subjective to an individual's background and experience – even among highly trained geologists. As an example, in a recent study, 412 different geoscientists (with different backgrounds and experience) were asked to interpret a seismic image. The results were surprisingly significant that only 21% of the participants interpreted the correct tectonic setting and only 23% highlighted the three main fault strands in the image (Bond et al., 2007). The results showed that the differences in interpretations were often related to an individual's previous experience – in other words, they "saw" in the image what they were used to seeing in their previous work.

The further steps of developing geological conceptual models and the assignment of the certainty (reliability) to these models add an additional degree of subjectivity. In a recent study, geothermal resource assessment is made based on analogies to the area and power density of developed fields (Cumming, 2011). In that study, probability of success in is defined as likelihood function of confidence in temperature, permeability, and fluid chemistry. The overall probability of success is calculated by multiplying the probabilities of these three components which results a lower probability value and increases the level of subjectivity.

2. METHODOLOGY

In this section, we present the two approaches that we have begun to develop: 1) value of information analysis (VOIA) and 2) exploration targeting. Neither method replaces the need for trained geologists and detailed conceptual models. All developers should determine their own risk tolerance. The two approaches presented here are additional tools that can be used in the decision-making process.

2.1 Value of Information Analysis

Many geoscientists request additional data to improve the reliability of decision making but the fundamental question to consider in data gathering process is: Is the cost of data-acquisition worth the improvement in decision making (Bratvold et al., 2009)? The VOIA methodology is designed to determine the impact of purchasing the proposed information against the overall value of the project. It considers the reliability of any particular data source and quantifies its value when making a decision with a highly uncertain outcome (Trainor-Guitton et al. 2014). VOIA uses Bayesian Inference statistics (Sato, 2011) and has been widely used for decision making since 1960 by many industries - from medicine (Wailoo et al., 2008; Wilson et al., 2010) to petroleum exploration (Ligero et al., 2005; Bratvold et al., 2009). It has also recently been applied for analyzing the value of magnetotelluric (MT) data in identifying production well placement in geothermal exploration (Trainor-Guitton et al., 2013a; Trainor-Guitton et al., 2014).

We developed the proposed approach in order to broaden the application to a larger suite of exploration activities during the pre-drilling phase. The decision to either conduct additional exploration, drill the first production well, or leave the field (Figure 1) is determined by evaluating the change in the value of the conceptual model after new information is obtained – relative to the cost of obtaining the information.

We started with a geothermal system definition that includes initial lithological, structural, hydrological and thermal parameters in the form of one or more conceptual models. Each conceptual model prior to the next decision will have two values to be estimated at this point: the reliability of the model and the risk of drilling (cost of an unsuccessful well) without additional exploration (Figure 2). The project will have an Expected Monetary Value (EMV) at the initial state. Next, a potential activity (or set of activities) is evaluated, and the impact of the resulting data on the reliability of a conceptual model is estimated by assigning an impact value. Impact values can be assigned by defining probability distribution functions, giving percentages or based on a scoring scale metric. Then, the reliability of the updated conceptual model (based on the data), and the risk (cost of drilling and additional exploration activity) is again estimated. These estimates come from a geologist or other experts with knowledge of the geologic structure and history (Trainor-Guitton et al., 2013b). This results a change in EMV of the project at the following state (Figure 2).

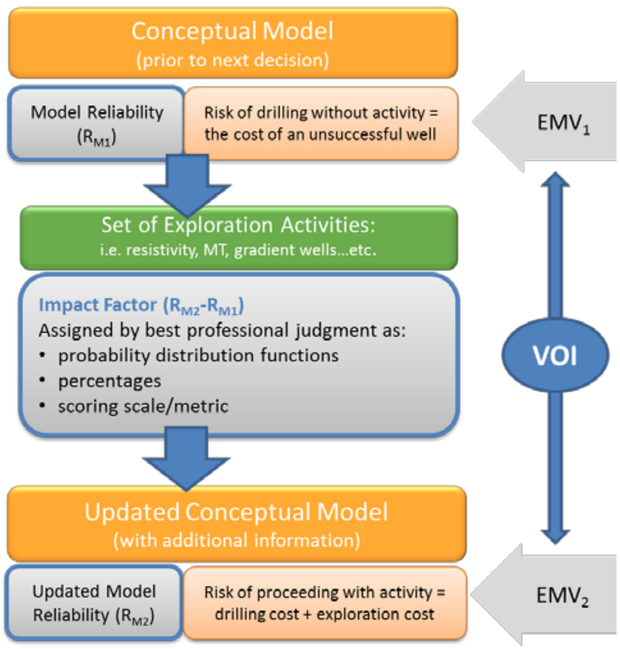

Figure 2: Decision-making with VOIA (The initial conceptual model has a reliability (R_{M1}) and risk value which results an EMV. Set of new activities is expected to make an impact on model to reach a higher reliability (R_{M2}) and EMV).

These input data – many of which are highly subjective (e.g., reliability of the two conceptual models and probability that the activity can improve the model) – are required in calculating the VOI. To calculate the value of conducting additional exploration, or VOI, the Net Present Value (NPV) of the project is estimated with and without the potential activity. The NPV is the sum of cash flow from a project devaluated to the present time with the required rate of return for the investment for the project (White et al., 1998).

$$NPV = \sum_{i=0}^{n} \frac{CF_i}{(1 + dr_i)} \tag{1}$$

where; i is the time of the cash flow which is divided in periods; CF_i is the cash flow for period *i*; and dr_i is the discount rate for period *i*.

Next, EMV of the project with and without the potential activity is calculated. In both cases, the EMV is calculated as the NPV times the probability of a successful well, or reliability of the model (R_M), less the risk (cost of a well), times the probability of an unsuccessful well ($1 – R_M$), as shown in Equation 2.

$$EMV = NPV \times (R_M) - \text{Risk} \times (1 - \text{R}_\text{M}) \tag{2}$$

Potential actions for at this point are; 1) leave the field (A_0), 2) drill the first production well with existing information (A_2) or 3) collect additional data prior to drilling and then proceed with drilling (A_3), as shown in Figure 3. The end product of each decision action is represented by the EMV of the action. Then, VOI can then be calculated as the difference between the two EMVs, as shown in Equations 3 and 4.

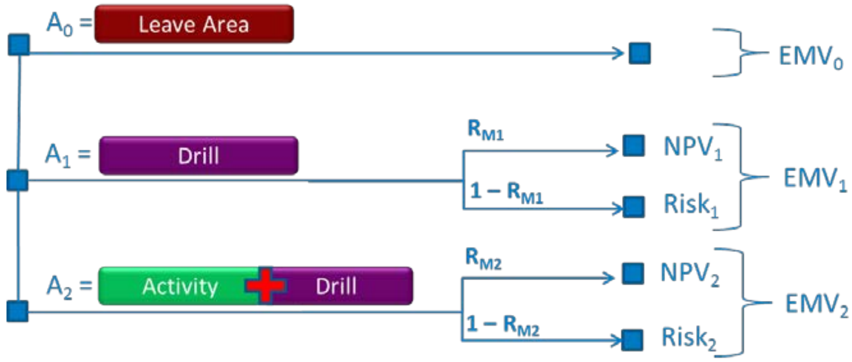

Figure 3: VOIA decision tree: A_0, A_1, A_2 are the decision actions; R_{M1} and R_{M2} are the probabilities of confidence in conceptual model. Gain and loss are defined NPV and value of risk respectively. Each decision action will result an EMV for the project.

$$VOI = [EMV_2] - [EMV_1] \tag{3}$$

$$VOI = [NPV_2 \times (R_{M2}) - \text{Risk}_2 \times (1 - \text{R}_{\text{M2}})] - [NPV_1 \times (R_{M1}) - \text{Risk}_1 \times (1 - \text{R}_{\text{M1}})] \tag{4}$$

The VOI depends on the degree of uncertainty (prior probability), economic impact of the decision (NPV), and reliability (conditional probabilities) of the information. The data acquisition is considered to be economic when the VOI is greater than the cost of exploration activity. VOI is highly dependent on NPV. In analysis the most likely value for NPV is used for decision making. The value of a particular set of information can be calculated to be insufficient or non-economic for a smaller size project but may be economic when the NPV of the project is larger. NPV is also limited to the resource potential and controlled by the total size of the geothermal reservoir.

As discussed in the introduction, there is subjectivity in the development of the conceptual models. There is additional subjectivity in assigning the probabilities of risk and success since; 1) there is no standard rubric or methodology for assigning risk, and 2) the people who assess the reliability of a conceptual model have their own biases. The level of subjectivity can be reduced in the exploration decision-making processes by using historical data statistics collected from analogous geological settings and geothermal play types.

2.2 Exploration Targeting Analysis

In Exploration Targeting Analysis (ETA) approach, as a first step we started with planning the exploration targets with the available data (exploration phase 1), to reach a target internal rate of return (IRR). Then, as a second step, we determined a minimum project IRR and adjusted the exploration targets to keep the IRR at desired minimum level. In third step, new data was added to the model (exploration phase 2, 3, 4) and exploration targets were updated based on these data resulting an updated IRR. In each phase calculated IRR was crosschecked with the minimum IRR to give the go/no-go decision for the project (Figure 4). Based on estimated total production capacity of the geothermal field, a target production curve was created as a function of reservoir temperature and total flow rate. The aim of the model was to keep the production target curve above the go/no-go curve with minimum required IRR of the project (Figure 5).

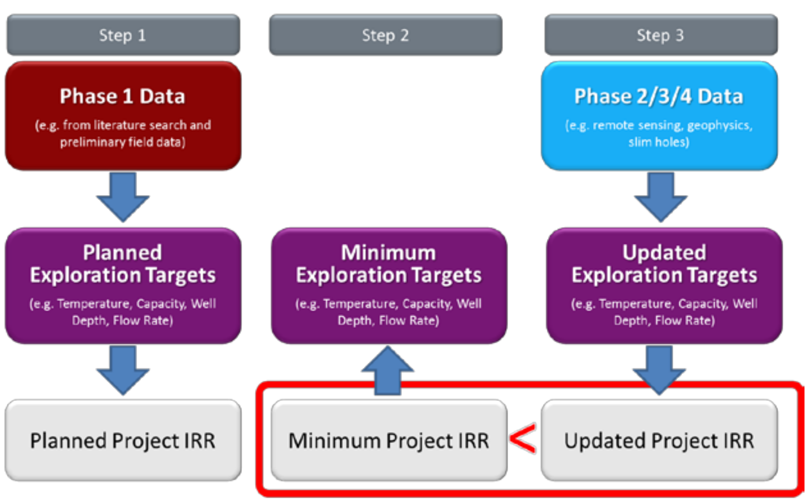

Figure 4: ETA decision flow chart (Step 1; Initial targeting, Step 2; Defining Go/No-Go decision points, Step 3; Updating model with new data and cross correlating calculated project IRR with minimum IRR)

Total production capacity of a geothermal area largely depends on the temperature, total volume, and productivity of the reservoir. In our model we assign input values for some technical and economic variables. Technical input variables include; desired total installed capacity, average target production capacity per well (MWe), minimum average temperature gradient, minimum re-injection temperature, and estimated reservoir temperature. Economic input variables include; exploration budget, well testing and development budget pump cost, unit power plant cost per MW and effective electricity sales price. Below, we give a brief description of some of the principal equations we used in developing the model, and then provide an example of its application at a given location using real (but slightly altered) exploration project data.

2.2.1 Defining Targets

Power generation capacity of a geothermal reservoir can be calculated by simple enthalpy equations. Enthalpy of a geothermal production well is basically a function of pressure, temperature, and phase of fluid. Production Enthalpy is the difference between the enthalpy of the produced fluid and the enthalpy of the dead state assuming the fluid is ambient temperature, ambient pressure, and liquid phase (Huenges, 2010).

$$Q = m \times c \times \Delta t \tag{5}$$

where; Q is the total heat flow, m is the total mass flow, c is the specific heat of geothermal fluid and Δt is the system temperature for the power plant. Mass flow is the total flow rate of single-phase geothermal fluid. System temperature is the difference between production and re-injection temperatures. Specific heat for geothermal fluid is taken as 1 kCal/kg°C in the model. Reservoir temperature is estimated by geothermometry calculations using the chemical composition of geothermal fluid, average temperature gradient extrapolations, and temperature logging. Flow-line temperature is usually not the same as the reservoir temperature, because there are heat losses through the fluid flow within the well bore. Therefore, we added a tolerance percentage to the flow-line temperature estimate in the model (i.e., 9% less than the reservoir temperature). The flow rate of a production well cannot be estimated properly before drilling the full-size production well. However, there are some methods of estimating the flow rate of full-size production wells from flow tests of slim-hole wells (Garg and Combs, 1998). If the reservoir conditions are sufficient, the flow rate of production wells can be adjusted to reach the desired capacity with a proper well design, pumping and well enhancement techniques (Sanyal et al. 2007). Electrical capacity of a geothermal reservoir can be estimated by the volumetric assessment methods and heat-in-place calculations (Garg and Combs, 2011).

2.2.2 Initial Project Budgeting and Financial Control

Initial project budgeting is required after the initial stage of exploration and includes estimation of exploration cost, drilling cost, development cost, power plant cost and operation and maintenance (O&M) cost. In the model, there are some assumptions related to project definition such as; project lifetime, project completion time, average annual O&M, and financial contingency as a percentage of total capital cost. Initial budgeting is made to estimate NPV and IRR of the project. In this model, the decision making is done based on project finances - namely by IRR, which is the nominal discount rate when NPV is equals to zero.

$$NPV = \sum_{i=0}^{n} \frac{CF_i}{(1 + IRR)} = 0 \tag{6}$$

Go/no-go decision criteria are defined by a team of geoscientists, engineers, economists and managers based on geological, technical and financial criteria affecting the IRR of the project. Capital expenditures (CAPEX) components used in the model are exploration cost, drilling cost, well pump cost, well testing and reservoir development cost, and power plant electro-mechanic (EM) cost. One of the most significant costs within the breakdown of the initial budget is the drilling cost. The cost of drilling increases with depth and the average current costs of geothermal wells (in million US dollars) were estimated as a function of reservoir depth by Lukawski et al., 2014.

$$Geothermal\_Well\_Cost = 1.72 \times 10^{-7} \times (Depth)^2 + (2.3 \times 10^{-3} \times Depth) - 0.62 \tag{7}$$

Annual revenue of the project is calculated by simply multiplying installed capacity with annual operation time and effective electricity sales price. Effective sales price can be estimated by a power purchase agreement (PPA) or feed-in-tariff (FIT). In the model the financial component was set as 100% equity financing. However, there is a certain amount of the financial contingency (i.e., 8% of CAPEX) to compensate additional costs that may result from debt financing or unexpected drilling risks. Although, there is no detailed breakdown of the operational expenditures (OPEX), it mainly consists of staff, maintenance, and pumping cost.

3. ETA EXAMPLE

To illustrate how the ETA could be used, we present an example. The values presented are modified from a real geothermal power plant project. Based on Phase 1 exploration activities and volumetric assessment of the geothermal reservoir, initial target production capacity is estimated to be 30 MW. Reservoir temperature is estimated to be 192°C by geothermometer calculations. The minimum average temperature gradient is targeted as up to 9°C/100m (Table 1). The re-Injection temperature limit is set as 70°C based on the scaling tendency of the geothermal fluid. The average drilling depth for production wells is calculated to be 2133m, to reach the target reservoir temperature, assuming average thermal gradient. Average production capacity of a single well is targeted as 4.5 MW, which would require at least seven production wells and four re-injection wells to reach the target total production capacity. At the targeted temperature, the required minimum total flow rate is calculated to be 562 L/s (at least 80 L/s/well) to reach 30 MW of production capacity with 175°C flow line temperature. Flow line temperature is taken 9% less than the reservoir temperature due to heat losses through the well bore and production line. Target IRR is calculated to be 17% based the initial cash flow of the project with desired parameters. Project completion time and project lifetime are assumed to be 5 years and 25 years respectively. The power purchase agreement price is assumed to be 10.5 cents/kWh. The project exploration budget is set as $5 million and the well testing (short term, long term & interference) budget is set as $250 thousand/well. No pumping is expected.

Also during Phase 1, the go/no-go decision is determined by setting the minimum IRR value – in this example, the go/no-go IRR is set as 13%. Setting this parameter does not dictate all other parameters, but only sets a limit within which all other parameters must fit. In our example, the temperature gradient and target reservoir temperature are defined to be 7.5°C/100m and 160°C respectively by the geoscientists (Table 1). Re-Injection temperature is estimated to be as low as 70°C to prevent scaling in the system and cooling the reservoir. In this case, the required minimum total flow rate is found to be 343 L/s from the enthalpy curve to reach 12 MW of production capacity with 145°C flow line temperature. Additional pump cost is added for achieving the minimum required flow rate. These inputs are not based on known data at this point; the exercise of developing this go/no-go scenario at this point in the project is to understand what a worse-case scenario might look like. Both the initial exploration targets (shown in red, Figure 5) and the go/no-go scenario (shown in grey dashed lines, Figure 5) can be plotted on a graph of temperature and flow rate.

After the Phase 1 estimates and go/no-go limits are set, additional exploration activities are conducted and a new set of data is collected in Phase 2 and Phase 3. With the new data, the target capacity is reduced to 20 MW and all other parameters are modified based on new estimations (Table 1). A new curve can be shown on the temperature-flowrate graph (purple curve, Figure 5). In Phase 4, temperature gradient and reservoir temperature data are updated from temperature gradient wells and slim-hole wells. The data from Phase 4 suggests a further reduction in estimated capacity, but the resulting IRR is still above the go/no-go minimum (green curve, Figure 5).

After drilling the first production well, the total capacity is reduced a third time down to 13 MW, with the IRR just barely above the go/no-go limit. Reservoir temperature is measured as 182°C by well logging. Minimum average temperature gradient target is measured as 8.5°C/100m (Table 1). Re-Injection Temperature limit is set to be 70°C based on scaling tendency of geothermal fluid. Average drilling depth for production wells is calculated to be 2141m. At least four production wells and two reinjection wells are required to reach the target total production capacity. Required minimum flow rate is found to be 279 L/s from the enthalpy curve and the wells are pumped to reach 13 MW of production capacity with 165°C flow line temperature (Table 1).

Table 1: Project constraints, assumptions for initial budgeting and target production values in different exploration phases (*Yellow cells are the input cells which are updated in each phase based on exploration data; blue cells are the assumption cells which are constant and not effected by exploration activities; grey cells has the calculated values based on input variables.*)

		Exploration Phases				
		Phase 1		Phase 2 & 3	Phase 4	Drilling
	Units	Target	Go-No/Go	Actual	Actual	Actual
Minimum Desired IRR	%	17.0%	13.0%	-	-	-
Calculated IRR	%	17.1%	13.1%	16.2%	14.3%	13.7%
Inputs						
Installed Power	MWe	30	12	20	15	13
Reservoir Temperature	°C	192	160	192	180	182
Minimum Average Temperature Gradient	°C/100m	9.00	7.50	9.00	8.00	8.50
Minimum Re-Injection Temperature	°C	70	70	70	70	70
Average Target Capacity per Well	MWe/well	4.5	3.0	4.0	4.0	3.5
Maximum Exploration Budget	$	5,000,000	3,000,000	5,000,000	3,000,000	3,000,000
Assumptions						
Project Lifetime	years	25	25	25	25	25
Project Completion Time	years	5	5	5	5	5
Utilization Factor	%	0.95	0.95	0.95	0.95	0.95
Pump cost	$/per well	0	500,000	0	0	500,000
Effective Sales Price (PPA or FIT)	cents/kWh	10.5	10.5	10.5	10.5	10.5
Power Plant (EM) Cost	$/MWe	1,500,000	1,500,000	1,500,000	1,500,000	1,500,000
Power Plant (O&M) Cost	$/MWh	9.00	10.00	9.00	9.00	10.00
Financial Contingency	% of total capital cost	8%	8%	8%	8%	8%
Conversion Constant	kCal/kWh	860	860	860	860	860
Specific Heat	kCal/kg°C	1	1	1	1	1
Density	kg/m³	998.15	998.15	998.15	998.15	998.15
Production Targets						
Number of Production Wells	#	7.0	4.0	5.0	4.0	4.0
Number of Re-Injection Wells	#	3.0	2.0	2.0	2.0	2.0
Max Drilling Budget per Well	$	4,551,115	4,551,115	4,551,115	5,062,505	4,584,641
Well Testing & Reservoir Development	$	1,750,000	1,000,000	1,250,000	1,000,000	1,000,000
Maximum Total Drilling Budget	$	45,511,154	27,306,692	31,857,808	30,375,027	27,507,846
Target Well Depth	m	2,133	2,133	2,133	2,250	2,141
Required Total Flow Rate	L/s	562	343	375	332	279

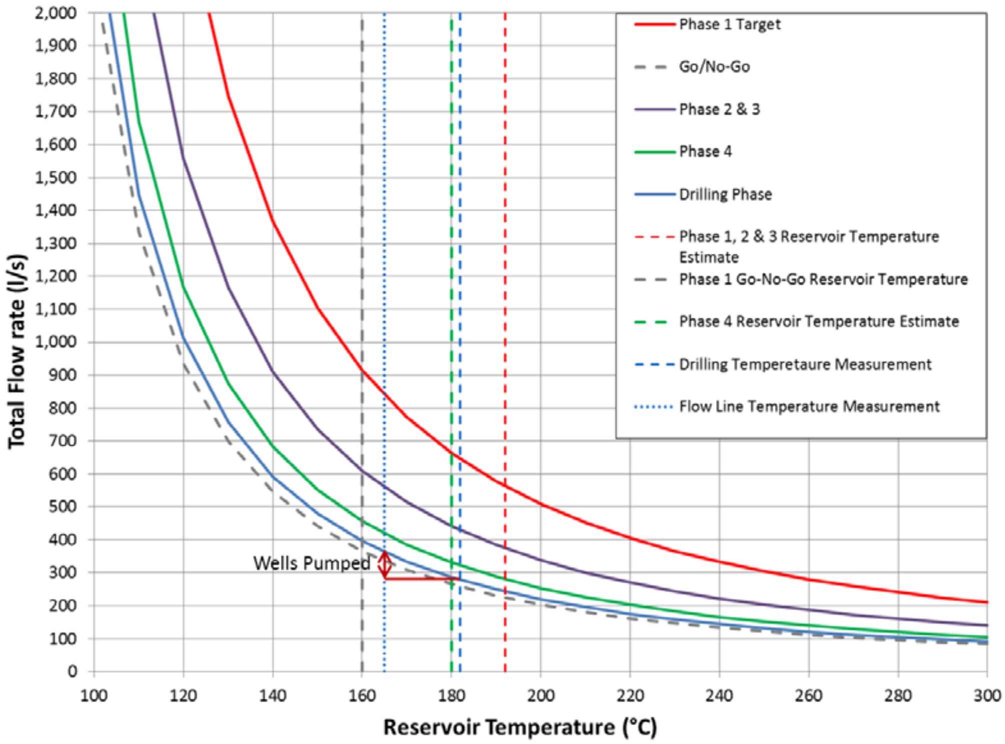

Figure 5: Reference production curves for different phases and reservoir temperature estimates (*Red Curve*; Phase 1 target production curve for 30 MW capacity, *Grey Dashed Curve*; 12 MW capacity production curve for go/no-go limit, *Purple Curve*; 20MW capacity production curve for phase 2&3, *Green Curve*; 15 MW capacity production curve for phase 4, *Blue curve*; actual production curve for 13 MW capacity after drilling first production wells, *Red Dashed Line*; 192°C reservoir temperature estimate for phase 1,2&3, *Green Dashed Line*; 180°C reservoir temperature estimate for phase 4, Blue *Dashed Line*; 182°C Reservoir temperature measurement during drilling phase, *Blue Dotted Line*; 165°C Flow line temperature measurement during drilling phase, *Grey Dashed Line*; 160°C go/no-go reservoir temperature limit) 165°C Flow line temperature was not sufficient to support 13 MW production capacity with the free flow rates and the wells were pumped to reach 13MW capacity and stay above the go/no-go curve.

4. RESULTS

In the scope of this study, two approaches were investigated to develop a best-practices methodology for objective geothermal exploration decision making at a given location, including go-no go decision points to help developers and investors in deciding when to give up on a location. Among those two approaches ETA is found to be less subjective than value of information analysis.

A sensitivity analysis was conducted to determine the variation in the results of IRR due to changes in five key input factors: temperature gradient, reservoir temperature, total capacity, sales price of electricity, and exploration cost (Figure 6).

The results of sensitivity analysis showed that:

- temperature gradient, reservoir temperature and electricity sale price have the largest effect on IRR
- exploration cost has a very minor effect on IRR
- drilling cost has a major effect on project IRR which is greater than the effect of electricity sales price (increasing reservoir temperature while keeping temperature gradient stable increases drilling cost and reduces IRR)
- total capacity estimate has a smaller effect on IRR than reservoir temperature and thermal gradient and its sensitivity curve makes a shift at positive 10% deviation from baseline. This is because of expected average capacity per well (an additional well is needed to achieve greater capacity which increases the total drilling cost and reduces IRR).

One other important observation is the direct correlation between reservoir temperature and average temperate gradient in calculating the project IRR. As an example, consider that, a project having 13MWe total capacity with 227°C reservoir temperature and 10.6°C/100m temperature gradient has 13.7% IRR. It requires a total flow rate of 160 L/s from four wells which produces at least a 40 L/s flow rate per well. Another project having the same total capacity with 136°C reservoir temperature and 6.4°C/100m temperature gradient has a the same IRR (13.7%) value. It requires a total flow rate of 640 L/s from four wells which produces at least a 160 L/s flow rate per well. In terms of project economics, both projects are equivalent to each other but the project with lower reservoir temperature and thermal gradient requires four times more flow rate per well. If the required flow rates are impractical to achieve from production wells— in terms of both reservoir parameters and well design— then the project may not be economically feasible. On the contrary, if higher flow rates can be achieved by additional pumping with proper casing design and reasonable reservoir drawdown, then the project may still be economically feasible.

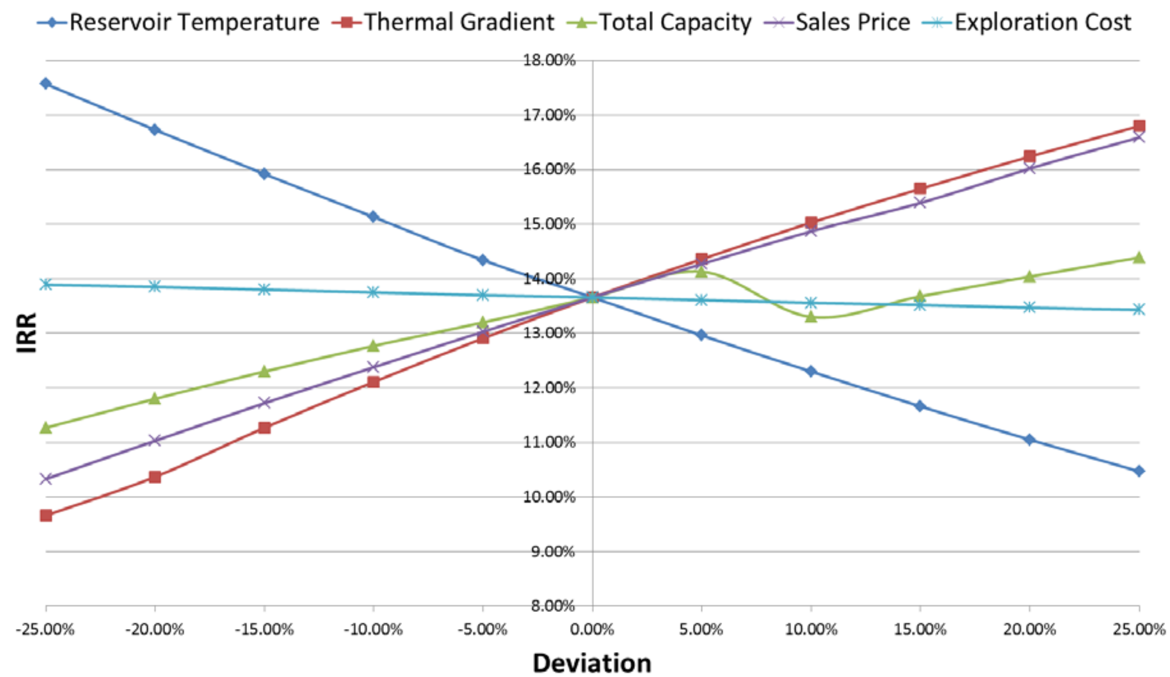

Figure 6: Sensitivity analysis for the 13 MW production capacity geothermal power plant project at drilling phase

High costs of data acquisition (i.e., MT. seismic, temperature gradient wells, slim-hole wells…etc.) at a specific phase of exploration may be misleading and lead developers to make incorrect decisions for the project. However, sensitivity analysis showed that exploration budget has a minor effect in changing IRR of the project. Thus, the impact of the activity for exploration targeting is more important than its cost. Drilling cost has more influence on IRR of the project than exploration cost. So it is important to estimate the productivity of the wells. Geothermal wells with low productivity can be enhanced with pumping, hydraulic fracturing, perforating or acidizing. This may add additional cost to the project but if the model supports the minimum required IRR value, the project may still be economic. The only variable in the sensitivity analysis, which cannot be controlled by exploration activities, is the effective sales price. The results showed that it has almost the same impact as thermal gradient on IRR. So, it can be said that, projects having higher sales prices (PPA or FIT) will have higher IRR.

5. DISCUSSION

The analysis of two different decision-making approaches is a first order analysis, and could benefit from additional work and modifications to make them more accurate and impactful. This initial work shows that VOIA has a high degree of subjectivity in assigning probabilities. The level of subjectivity can be decreased by defining probability distribution functions, assigning impact buckets or reliability percentages, which may allow for increased reproducibility by multiple trained geologists making independent assessments. The second approach is determined to be less subjective because numerical inputs come from collected data. These, too, have an element of subjectivity, however, as each geologist may interpret data differently, as indicated. Exploration targets and go/no-go limits are calculated from these input parameters, and estimates for geological constraints are updated in every exploration phase.

This initial work shows that VOIA has a high degree of subjectivity in assigning probabilities. The level of subjectivity can be decreased by using historical data statistics collected from analogous geological settings and geothermal play types, or creating a scoring scale metric for specific set of activities. One outcome of the VOIA approach is the effect of project capacity on the calculated value of the data. Consequently, a set of exploration activities may have higher VOI for larger capacity projects while they are not found to be economic to purchase for smaller size projects.

ETA approach is appears to be less subjective and more reproducible because numerical inputs come from collected data but it still has significant uncertainty. The input variables used in the ETA model is not always a definite numbers and they may have a range of values. In this case *Monte Carlo Simulation* can be used to reduce the uncertainties in the input variables. In the ETA model, energy conversion calculations are based on an average enthalpy value. It may be different in a double-phase flow having different brine-gas ratio (enthalpy of steam is much greater than enthalpy of brine). Brine gas ratio is controlled by flashing point within wellbore and can also be adjusted by flow line pressure through a steam separator or placing a submersible pump below the flashing point of the production well.

The model is developed excludes the drilling risk and assumes 100% equity financing. However, a certain percentage of financial contingency is added to the model to compensate for additional costs from unexpected drilling risks and debt financing. The Geothermal Electricity Technology Evaluation Model (GETEM) and the System Advisor Model (SAM) tools can be used for a better financial estimate (Blair et al., 2014).

Typically, companies explore several areas at the same time in the early stages of exploration, narrowing down their number of prospects at each phase, allowing them to target the top areas in their portfolio prior to drilling. Although the examples outline above are shown for a single area, these two approaches could be used in this multi-area approach to exploration.

6. CONCLUSIONS

Our effort in making these analyses is to develop a methodology for more objective geothermal exploration decision making at a given location to help developers and investors. Geothermal exploration projects have a significant amount of risk associated with uncertainties encountered in the discovery of a new resource. Before staring an exploration project, developers should determine their own risk tolerance. Two important challenges for project deployment are 1) understanding when and how to proceed in an exploration program, and 2) when to walk away from a site. In this scope, we tried to analyze two different approaches and concluded that, the VOIA and exploration targeting methods can be used as complementary studies in decision making for evaluating a new geothermal resource. It may be a better approach to start with VOIA approach in early stages by checking parameters and results of ETA approach because exploration targeting method is so dependent on flow rates and it is not practical to estimate flow rates in early stages. If calculations show unrealistic flow rates with very confident temperature estimates, the developer may decide to discontinue exploration. NPV of the project may also be estimated using ETA approach and that value may be used in the probabilistic calculations of VOIA. In later stages the decision making may then switch to exploration targeting to make decisions on drillings and implementation of the project. Thus, complementary use of VOIA and ETA with control of IRR can be a useful decisions making tool in geothermal exploration projects. This may also help to facilitate communication between project managers and exploration geologists in making objective go/no-go decisions throughout the different project phases.

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