Risk Management for Recoverable Thermal Energy Using a Probabilistic Decision Analysis Approach

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ABSTRACT

The financial risks involved in developing a geothermal resource often prove difficult to overcome because of perceived large uncertainties in the decisions that need to be made. These types of risk management decisions are often complex, involving uncertainties in the geothermal resource, availability of sufficient water, costs of development and production, protection of the environment, and uncertainties in the local energy needs. Probabilistic decision analysis is ideally suited to manage expectations and associated uncertainties of a decision problem, and can be applied successfully to choose the optimal decision at each stage of geothermal resource development, which could include continued investment and cessation of development. An integrated decision analysis approach involves building decision models in the early stages of a geothermal project, which are associated with relatively large uncertainties, and refining the decision model for subsequent decisions that are made at each phase of development. At each phase of development the best decision is made in the face of the uncertainties that currently exist. This approach to sequential risk management results in better understanding of the full context of the decision options available, and hence more effective development of geothermal resources.

1.0 Introduction

There is vast production potential in geothermal sources of energy in the United States and worldwide. However, there are also large financial risks involved with bringing a resource to market because of uncertainties in the location, magnitude, and development of a potential geothermal energy source. The situation is not dissimilar to oil speculation early in the last century that saw wildcatting efforts to find oil reserves that led to either oil production and hence energy production with associated financial benefits, or large financial losses. The financial risks involved have made it difficult to bring geothermal energy projects to market.

There are several stages of a geothermal play that increase in cost with each phase of development, but also reduce potential risk at each phase. These phases can be described in terms of the potential to develop a geothermal resource based on an understanding of the magmatic, mantel or radiogenic (MMR) energy potential.

PHASE I Geothermal Play

Requirements to advance from geothermal play are:

- Desk top study of a geothermal play
- Statistical analysis to determine MMR gas exploration sample number and placement.

PHASE II Inferred Geothermal Resource

Requirements to advance to Inferred Geothermal Resource are:

- Surface geophysical exploration
- Geochemical investigation – aqueous and gas
- Geologic field investigation
- Estimation of Thermal Energy in Place by probabilistic analysis.

PHASE III Indicated Geothermal Resource

Requirements to advance Indicated Geothermal Resources are:

- Surface and subsurface geophysical study,
- Further temperature studies (liquid, mineral and MMR gas geothermometery),
- Thermal conductivity and heat flow determination
- Temperature gradient hole
- Further probabilistic analysis of reservoir to estimate recoverable electrical energy
- Determination and securing of modifying factors such as legal, environmental, land access, social and governmental factors.

Phase IV Measured Geothermal Resource and Probable Reserve

Requirements to advance to measured Geothermal Resource and Proven Reserve are:

- Petrologic sampling and analysis,
- Drilling of slim holes
- Flow testing
- Determination and securing of modifying factors such as production, economic, power purchase agreement, and marketing.

PHASE V Proven Geothermal Reserve

Requirements to advance to Proven Geothermal Resource into production are:

- Completion of production and injection wells, plant construction, utility interface, and production startup

The costs of the early phases are on the order of tens of thousands of dollars, but the costs of later phases are hundreds of thousands to millions of dollars. The risks are greater at the beginning, although the amount of money at stake is lower. Nevertheless, there is a general reluctance to pursue geothermal plays, and there is a reluctance to pursue further development without some reduction in risk.

To address the risk issues and increase the potential benefit of recoverable geothermal energy, there is a need to start to address risk management from the initial stages of geothermal exploration when a geothermal play has been identified as an inferred geothermal or indicated resource. A potentially useful option is to characterize and model the geothermal resource, associated uncertainties, costs of characterization and development and potential liabilities associated with failure, in a comprehensive decision analysis support system. This approach, using probabilistic decision analysis modeling, would involve more refined modeling at each Phase as more information or data are collected, with the accompanying reduction in uncertainty at each step. In the initial stages the model will rely on more limited, possibly near-surface, characterization data, hence the probabilistic models will include greater uncertainty. As more information and data are collected the model is refined and uncertainty in the model and in the decisions is reduced. At each Phase or step, decisions are made to continue or abandon the geothermal options. This decision depends on both the expected success of the project and the uncertainty. This type of decision modeling approach includes estimation of the geothermal resource coupled with the cost and liability model in an integrated system so that effective uncertainty analysis, sensitivity analysis, and risk management can be performed. This would lead to more effective decision making concerning the viability of a potential geothermal energy resource. This type of analysis has been performed for environmental problems as diverse as sustainable land re-use (Vega et al, 2009), stream water quality assessment (Allan, 2011), unexploded ordnance (Black et al, 2008), and radioactive waste disposal (Crowe et al, 2002), and can be used successfully to characterize and effectively manage the risks associated with geothermal energy plays.

2.0 Previous Work

Previous efforts to address risk management for geothermal energy projects have focused primarily on modeling the resource from available data and information. These efforts have focused on probabilistic modeling of the resource itself. This is often based on limited data and use of analytical models such as the Volumetric "Heat in Place" model (e.g., Garg and Combs, 2010). Probability distributions have been specified for input variables and Monte Carlo simulation is subsequently performed. Examples of the use of this approach to modeling can be seen, for example, in the works of Garg and Combs (2010), Williams, Reed and Mariner (2008), and Williams (2007). Garg and Combs identify two sets of parameters (variables) that require specification. The first set of parameters are site-specific:

- Reservoir area
- Reservoir depth
- Reservoir thickness
- Reservoir temperature
- Thermal recovery factor.

The second set of parameters are considered less variable and can potentially be estimated from existing projects:

- Volumetric heat capacity
- Rejection temperature (reference temperature)
- Conversion efficiency
- Plant or project life
- Plant load factor.

The literature clearly indicates concerns about specification of probability distributions in the early phases of exploration. For example, it is noted in Garg and Combs that "different distributions (uniform vs. triangular vs. Gaussian vs. log-normal, etc.) will give different answers; thus, providing additional uncertainty in the estimation process". The references above (Garg and Combs, Williams et al., Williams) describe the poor results obtained for probabilistic estimates without adequate site-specific information and mention that the method is often misused. There is significant potential for improvement in understanding uncertainty in these types of models, and lessons can be learned where probabilistic modeling has been used in other fields.

These types of issues can be overcome, and need to be overcome, so that effective modeling with uncertainty can be performed. The approach should not involve arbitrarily choosing a distributional form (triangular, uniform, normal, etc.), but, instead, understanding the available data/information to estimate the most appropriate distribution. This can be done with statistical analysis of data, with methods that take into account secondary sources of data, or with expert elicitation. It is critical that proper input distributions are specified if the models are expected to effectively support risk management decisions. This issue is analogous to what is sometimes referred to as "Garbage In, Garbage Out" following the early development of computers (Babbage, 1864). Poor specification of input distributions can lead to poor modeling performance, and hence poor decision making.

Another issue that is raised in Sanyal and Sarmiento (2005) is the challenges associated with numerical modeling: "While numerical simulation is more sophisticated than the volumetric method, the volumetric approach can be readily conducted in a rigorously probabilistic way while the numerical simulation cannot (Sanyal and Sarmiento, 2005 p 467)." Sarmiento and Bjornsson (2007) suggest instead that numerical modeling is a reasonable approach: "There is no doubt that numerical modeling is still the best approach in conducting resource evaluation". However, they go on to say that numerical modeling needs more detailed knowledge of the reservoir parameters to be assigned to the various cells in the numerical grid.

The choice between analytical and numerical modeling can be framed in terms of the associating needs of the model with the right tools for the job. Regarding the issue of numerical modeling, there are many fields of earth science modeling that involve the use of numerical grids. Typical "process-level" modeling often involves fine grids. In these situations the models are often parameter rich and data poor, which can lead to the types of issue discussed in Sarmiento and Bjornsson. However, a question that is not addressed in process-level modeling is the need for a refined model. In this context, process-level modeling is often associated with the term "bottom-up" modeling. An alternative approach is to use "top-down" modeling, which is aligned with "systems-level" modeling and decision analysis modeling. This type of approach is espoused in probabilistic simulation programs such as GoldSim, which emphasizes the importance of top-down systems-level modeling in which uncertainty is properly captured and analyzed. The basic philosophy of this type of modeling is consistent with the idea that "all models should be as simple as possible, but no simpler" (Morgan and Henrion, 1990). Systems-level modeling can include analytical or numerical solutions to problems, but if a numerical approach is taken then the grid that is used is much coarser than in process-level modeling.

The goal of systems-level modeling is to focus on the important aspects of a model to support decision making. Sanyal and Sarmiento address aspects of decision making by breaking the outcome space into three distinct options of Proved Reserves, Probable Reserves, and Possible Reserves. The distinctions are made only with respect to the resource, and does not consider other factors that should be important for the decision making process. In a systems-level model, the modeling effort is driven by the decisions, and uncertainty and sensitivity analysis are used to evaluate the model and determine how much more and which type of information is needed to improve the model iteratively until the decision can be made with sufficient confidence. In addition, this approach can help optimize across the parameter space, so that the best overall decision can be made.

3.0 A Risk Management Approach

One of the key challenges in practice is convincing stakeholders that it is worthwhile to invest in developing a geothermal reserve, when uncertainty about the reserve's potential is high. Use of a formal decision analysis framework can help provide investors with a defensible strategy, by carefully quantifying uncertainties and utilizing them to understand cost-benefit tradeoffs.

Lessons can be learned from other areas in which similar approaches have been taken. This includes areas as diverse as sustainable land re-use, watershed management, radioactive waste disposal. The approach is based on Bayesian statistical decision theory (e.g., Morgan and Henrion, 1990), and involves probabilistic modeling, characterization of costs, liabilities and value judgments, and updating or calibrating with data as necessary, to find the optimal solution. A summary of possible methods is provided in Black and Stockton (2009). A decision analysis follows a sequence of iterative steps, which are also depicted in Figure 1:

1. Understand the decision context,
2. Define decision objectives and identify measurable attributes,
3. Identify possible decision paths (options),
4. Evaluate decision paths and assess the impact of uncertainty,
5. Select a decision path or collect more information if the uncertainty is too great (and iterate).

This iteration implied in Figure 1 ends when sufficient information has been collected to ensure that a suitably confident decision can be made.

The objectives of decision analysis are to logically and defensibly reduce risk, to allocate and prioritize resources, to understand the confidence with which a decision can be made, and to provide insights into complex problems and the important drivers that affect decision-making. From a risk reduction perspective decision analysis is an optimization – it is used to minimize the risk from the various actions that might be taken. A decision analysis informs the decision-making process by quantifying common sense through formal, logical, defensible, and well-established methods. An effective decision analysis focuses on the important aspects of a decision problem, and leads to development of cost-effective strategies or solutions.

The decision analysis will not 'make the decision'. Decision-makers make decisions. The decision analysis is a tool that supports integrated risk management. The decision analysis will clarify the complex issues associated with this difficult decision,

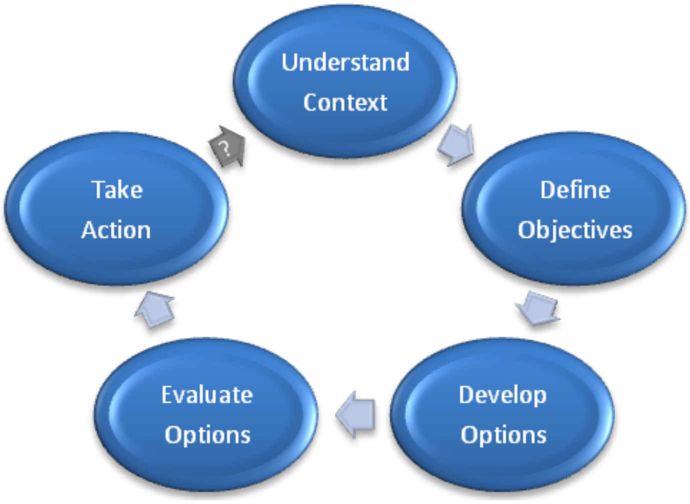

Figure 1. General decision analysis process.

and will provide a defensible, transparent process to support any subsequent decisions that are made. Decision analysis is the appropriate tool for quantifying risks, so that decisions that are made are transparent, defensible, and understood.

There are nuances to deal with in this type of decision analysis modeling. For example, it is critical to properly address specification of input distributions using formal statistical methods that address expected values, uncertainty, and account for spatio-temporal scaling and correlation. If correlation is not accounted for, or if the wrong spatio-temporal scale is used in specification, then uncertainty estimates are usually over-predicted, and sometimes by several orders of magnitude. This is not helpful for understanding the system, or for decision making.

Proper specification can be done using statistical estimation if data are available, or using statistical meta-analysis tools if secondary data or literature information are available, or using expert elicitation if there are no data but there is expert knowledge. A combination of approaches is often used for model parameters to accommodate the range of possible available data and information. This specification step is critical. If probability distributions are specified poorly, then the outcome of the modeling is not useful for estimating the resource, and hence is not useful for risk management.

It is also critical to consider the full range of decision options so that costs associated with development are included for different options. The cost model should include economic (financial), environmental and stakeholder issues so that all relevant costs and liabilities are included. The goal is to build effective systems-level decision analysis tools that will allow potential investors and developers to gain insight into the main drivers for the risks involved, and to make fully informed decisions on the potential benefits or risks associated with a geothermal energy production project.

When constructed properly, complete systems-level decision analysis models are subjected to:

- effective uncertainty analysis to determine if a decision can be made with sufficient confidence
- effective sensitivity analysis to identify parameters that are most important in the model, and hence in the decisions to be made
- value of information analysis to determine which and how much data needs to be collected.

This is the iterative process of decision analysis modeling, which is also fully consistent with the Scientific Method. It leads to optimization of data collection efforts, and optimization of decisions that need to be made. For geothermal problems, this approach can be built initially to address Phase I issues, and can be updated as data/information are collected during each Phase of development. At each Phase, a decision can be made of whether to continue, and, if so, how much more information to collect.

Issues that might come to the fore include resource characterization modeling and costs, drilling costs, available water for sustaining the system, optimization of water resources so that sustainability is maintained, the cost of water rights to allow adequate access to shallow low temperature groundwater or surface water, costs of development, costs of environmental compliance, affects on the environment (environmental regulations), and benefits for the affected community.

Numerical modeling can be performed to characterize the resource, but this should only be necessary if the analytical Volumetric “Heat in Place” models are considered insufficient. For example, probabilistic models, such as those utilized in Garg and Combs (2010 and 2011), provide a basis for addressing uncertainty in energy production potential. Or, numerical models as suggested in Sarmiento and Bjornsson (2007) could be used. With a model in place, a decision analysis model can then be employed that carefully describes the risks associated with any decisions. In order to construct the decision model, it is crucial to model the potential costs as well as the potential payoffs associated with decisions. Costs may also have uncertainty associated with them and might also benefit from being modeled probabilistically. For example, drilling costs will depend on ease of accessibility to good drilling locations, required drilling depth, geology type, etc.

One of the primary benefits of constructing a formal decision analysis model is that it provides a basis for explicitly defining the *value of information*. Data collection costs money, so before any data collection efforts are pursued, it should be clear that the benefits of the data – decreased uncertainty – outweigh the costs. Further, the data collection should be designed to minimize the risk of subsequent decisions. That is, there may be several uncertain components in the model, each of which may in turn lead to uncertainty regarding energy generation potential as well as future costs for subsequent data collection efforts, capital costs, and maintenance costs. Data collection efforts need to be aimed at reducing uncertainty associated with *decisions*, and not just geology.

4.0 General Decision Analysis Model for Geothermal Energy

A crude depiction of a decision analysis, or cost-benefit analysis, for a geothermal situation is presented in Figure 2 below. The top graph depicts the potential benefit of tapping the geothermal reserve, and a probability-weighted cost of proceeding with an investigation. That is, as data are collected, if evidence indicates poor energy potential, then the decision will be to proceed no further (and spend no more money investigating). As energy potential increases, there is increased likelihood (and thus increased cost) of proceeding to further investigation. Costs outweigh benefits for low energy potentials, and vice-versa for high energy potentials.

In order to decide whether to proceed with an initial data collection effort, the decision risk must be computed by accounting for uncertainty about the difference between benefit and cost. The lower graph depicts three different potential initial uncertainty distributions for the energy potential. Prior 1 (furthest left) indicates near certainty that cost will outweigh benefit, so the play should not be exercised. Prior 2 (furthest right) indicates near certainty that benefit will outweigh cost, so the play should be exercised. Prior 3 (middle) is the interesting case, where there is reasonably high probability that cost will outweigh benefit, along with a lower probability that benefit will greatly outweigh cost. In this case, perhaps further data is needed to make a sufficiently confident decision, or perhaps a close decision can be made already The decision risk calculation, and the accompanying sensitivity analysis will provide insights into the best decision option to pursue in this case. The sensitivity analysis provides some understanding of the important parameters that affect the decision analysis. This covers all the parameters, including the hydro-geological modeling and the cost and value judgment models. For example, perhaps the cost of obtaining water is greater than the cost of drilling. Or, perhaps the benefit to the community far outweighs the economic costs of construction. The most sensitive parameters are not necessarily the ones for which further data collection is performed. This is evaluated through a trade-off between the uncertainty reduction that can be achieved and the cost of collecting the data.

These types of models can be extended further to incorporate:

1. Other sources of information.
    a. Alternate conceptual models for the geology.
    b. Historical information about components of the model (e.g., expert elicitation).
    c. Information or data from other similar sites.
2. Other parameters of interest to investors, related to production costs could include:
    a. Accessibility costs.
    b. Drilling costs.
    c. Consumptive use of water.
    d. Environmental regulations, water rights, and associated costs and liabilities.
    e. Economic benefits to the public.

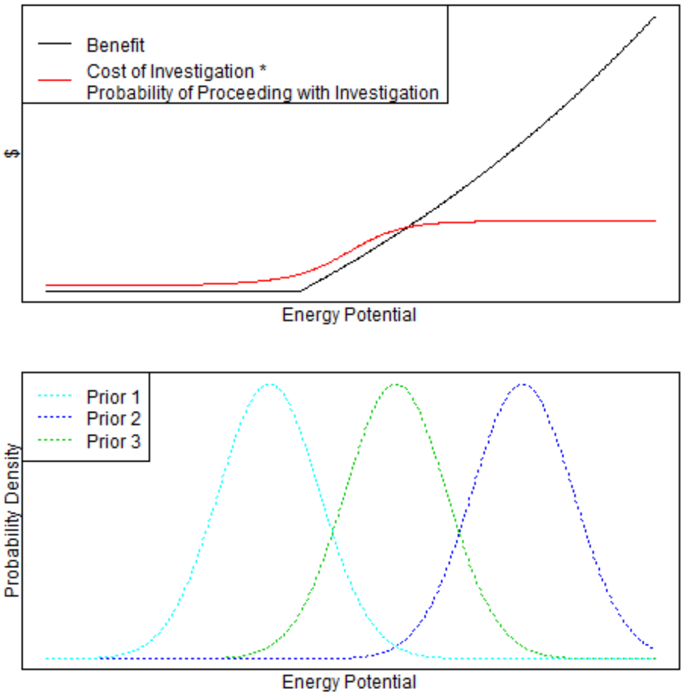

Figure 2. Simplified Cost-Benefit Analysis.

The important point is that this type of decision analysis model can, and should, factor in all economic, environmental, and stakeholder components so that the most effective decisions can be made. This might include costs associated with the consumptive use of water for cooling the working fluid as part of the sustainability equation. This may require securing water rights to ensure adequate access to shallow low-temperature groundwater or surface water. The general need is to establish a risk management approach for Recoverable Thermal Energy (MegaWatts) after initial stages of geothermal exploration when a geothermal play has been identified as an inferred geothermal or indicated resource (The Geothermal Reporting Code, Australia 2010).

From a modeling perspective, a general framework program can be developed to directly support decisions that are made at each Phase of the geothermal evaluation process. Decision analysis frameworks exist for a variety of other applications, and could be adapted to this problem. There would be clear benefits in the long run as more data/information and projects are brought into the system. The framework would allow for different (competing) geologic models or models of the resource, and alternative models for development of the resource. Overall, this cost-benefit approach would help optimize resources, and could be adapted to prioritize development among potential resources. The net effect will be reduced risk for investors, and hence for all other stakeholders.

5.0 Conclusions and Future Development

The primary focus of modeling and uncertainty assessment has often been on defining the potential resource, which is most often presented and performed using the Volumetric "Heat in Place" analytical model coupled with probability distributions specified for input variables and Monte Carlo simulation. However, the type of resource modeling performed is not as important as its role in an overall risk management approach to decision making for potential geothermal plays. Much of the literature is focused on resource modeling including concerns about analytical and numerical modeling, and concerns about perceived inadequacies of statistical estimation of input distributions and not on value judgments and cost consequences of the decisions that need to be made at each Phase of the geothermal project. That is, resource modeling does not usually address the larger decision context. Risk management is an ideal tool to extend this line of thinking from modeling the resource to placing the resource modeling within the context of the larger decision analysis that must take place.

An integrated risk management strategy is needed to support an inferred or indicated geothermal resource. This is critical for the long-term success of geothermal energy, otherwise, the effect of large uncertainty will limit the willingness of financial investors to participate and a resource will be lost, or at least underplayed. This could have deleterious effects on the energy future of the country as we continue to move away from a fossil-fuel based economy.

Integrated risk management should be supported by quantitative analysis, which is most appropriately performed using decision analysis using systems-level modeling with uncertainty properly characterized. Decision analysis is a formal method that when implemented fully, is aimed at minimizing risk. In the context of the need for an integrated approach to risk management, decision analysis provides the quantitative methods for minimizing business risk in the face of potential liability, with a particular emphasis on the large potential environmental liabilities with which the geothermal industry is faced.

This requires a shift in strategy from the current approach, which usually focuses on characterization of a resource, and not on other factors that are important for the risk management decision that needs to be made such as social and environmental value judgments and the cost consequences of the decision options. Use of decision analysis modeling that includes a model of the resource, of the water balance cycle, of environmental liabilities and social benefits, and of the plant development and energy production will result in more effective planning for managing business risk from potential liabilities and benefits.

A framework program can be developed similar to those used in other areas (e.g., land re-use, water quality, radioactive waste management), so that the basic decision analysis model does not change, but the details of each new project changes. With each new project the decision analysis framework will be enhanced with project-specific information that could be shared across projects. Different models can be made available within the framework program as the specific project demands. This approach will lead to more consistent risk management for geothermal plays now and into the future.

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