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A Multi-Tiered System Dynamics Approach for Geothermal Systems Analysis and Evaluation

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ABSTRACT

Compared to other renewable energies such as solar, wind, and hydroelectric, geothermal energy is unique with regards to our ability to predict the economic viability of a particular site or technology. For instance, measuring wind speed for the purposes of assessing a site’s potential for a wind farm is relatively simple when compared to determining the extractable energy from an enhanced geothermal system (EGS) site. While this difficulty does not diminish the promise of geothermal energy production, it does require additional analyses to deal with the higher levels of uncertainty that exist throughout the characterization, development, and deployment process. The cost of not fully understanding how uncertainty in each of these phases impacts the probability of successfully developing a project comes in lower investment rates and longer development times. It is only by either reducing uncertainty or increasing our understanding of the implications of uncertainty that we can hope to more accurately address geothermal performance and its economic viability.

To address this issue, we have developed an integrated systems modeling tool that allows a user to perform real-time tradeoff and scenario analyses. This ability allows interested parties (e.g., engineers, project planners, potential investors) to identify the optimal solution space for a given set of site characteristics, and power plant and well configurations. The tool also allows for identifying key areas of uncertainty that if better understood, would provide the largest gain in understanding and predictability and will ultimately be able to identify and assess the set of physical, technological, and economic obstacles that need to be overcome for a geothermal project to become market competitive. The integrated model framework is built using a system dynamics (SD) approach that allows for the simulation and quantification of system and sub-system relationships in order to capture the feedbacks and delays that create the complexity and non-linear behavior that is so difficult to contend with. In this way, the model is able to simulate the efficacy of investing time and/or money into reducing areas of uncertainty while assessing the timing, cost, and market competitiveness of geothermal energy production.

Introduction

Geothermal energy development requires assessment of the quality and accessibility of a resource, the available materials, services, and technologies, the demand for power, and the economics of the entire process. Each of these areas represents a complex system of systems that can be difficult to evaluate. Adding to this difficulty is the fact that these systems are dependent on the behavior and states of the other systems and sub-systems that comprise the whole.

For example, the quality of an EGS site could be defined using the depth, temperature, and rock type of the reservoir. The depth, temperature, and rock type can also be used to define the ease of accessibility to the resource, which in turn has a large influence on the economics of the project. If one wanted to evaluate the depth where the additional cost of drilling becomes greater than the gain in revenue that would result from accessing a higher temperature resource, the set of systems and sub-systems that influence the costs, revenue streams, and power production would have to be considered. One of those systems would be the type of power plant that would be used to convert the extracted heat to usable electricity. But one cannot design the power plant with its various efficiencies and costs without knowing the working temperature of the geofluid, which in this example is a function of depth. What this illustrates is systems-level feedback that results in non-linear and unintuitive behavior that makes integrated assessment geothermal energy production so difficult. This concept is shown in Figure 1, overleaf.

To perform a complete analysis, a full suite of the systems and sub-systems that comprise the problem would need to be included, resulting in multi-tiered dependency structures with multiple feedback loops. In addition, as the dimensionality of the dependency structure and the number of feedback loops increases, so too does the level of uncertainty. In fact, with regards to assessing a project,
it is the level of uncertainty that is most difficult to contend with as opposed to the non-linear behavior of the integrated systems. However, the need to make these assessments is paramount if geothermal energy production is to become cost competitive, and will most likely always precede the ability of science to reduce uncertainty to a level that could be considered negligible. From this, we can pontificate about how uncertainty must be treated when assessing geothermal energy production using a simple but important statement:

>The existence of uncertainty must be taken as a working-condition for geothermal energy production development.

Thus, a need exists to develop tools and analysis methods that include uncertainty in its evaluation. The tools and methods must support assessments at each step so that the decisions that are based on those assessments consider the degree of uncertainty and more importantly, the implications of making that decision if the assessment is wrong.

**Objective**

To address this need, we are developing an integrated systems modeling tool that allows a user to perform tradeoff and scenario assessments for a variety of geothermal applications. Part of a multi-disciplinary development process, the objective is to use a system dynamics approach to develop an integrated simulation and analysis tool that will:

1. Bound the multi-dimensional technical and economic parameter space for different geothermal technologies as a function of location, heat extraction technology, geologic conditions, power plant type and configuration, available resources, and economics.
2. Identify the key gaps in understanding and technology that pertain to exploration, site selection, site development, heat extraction, and heat conversion.
3. Identify the integrated technical and economic bottle necks and uncertainties associated with developing a geothermal resource.
4. Incorporate spatial variability in the evaluation of a geothermal resource.

The tool also allows for identifying key areas of uncertainty that if better understood, would provide the largest gain in understanding and predictability and to identify and assess the set of physical, technological, and economic obstacles that need to be overcome for a geothermal project to become cost competitive.

The tool is being developed with the input and guidance of industry experts, academics, and other DOE researchers and scientists. The initial version of the model was released earlier this year, with future versions to be released as functional plateaus are reached. This allows for transparent development and vetting of the model and its parameters by stakeholders and interested parties who can provide ongoing feedback for improving the tool in the years to come. Due to the variety of users and evaluators, the model also includes a graphical user interface that makes running and using the model relatively easy. In addition to the technical feedback, stakeholders are also asked to comment on the interface as well as the usability of the model. At its completion, we envision this tool to be a fully integrated computer simulation model that will allow analysis over a variety of spatial, temporal, and technological scales.

**Methods**

In order to define the multi-dimensional technical and economic parameter space, we have identified six top-level systems that must be assessed:

- Heat Extraction
- Heat Conversion
- Well Field
- Spatial Constraints
- Economics
- Institutional Constraints

If a geothermal production site is to be cost competitive, it must be able to, in a cost effective manner and within any spatial or institutional constraints, develop a well field, extract heat from the resource, convert that heat into usable energy, and deliver that energy to the user. In order to capture the integrated dynamics of these top-level systems, the model is being developed using a system dynamics (Forrester, 1971) (SD) approach that allows for simulating and quantifying the temporal integrated behavior of disparate yet connected systems and sub-systems; the collection of which makes up the ‘global’ system of interest. SD models predict the macro-behavior of the global system by simulating the collective behavior of the sub-systems and the associated feedbacks and delays between those systems.

The model architecture uses a multi-tiered modular approach. Tier 1 consists of the six top-level systems described above (Figure 2). Tier 2 in turn, consists of the sub-systems that make up and describe the Tier 1 systems. Each successive Tier provides...
more detail and resolution than its parent Tier with the number of Tiers for any one system being based on its relative importance within the global system. Figure 3 illustrates this concept by showing how detail increases with each successive Tier for the Tier 2 Drilling Technology sub-system of the Tier 1 Well Field system. Development of the model to date has concentrated on Tier 1 and Tier 2 functionality for EGS, with higher Tier functionality to be developed as suggested by the stakeholder input. The modular development approach allows for maximum flexibility as future functionality is added.

At present, the model simulates heat and fluid flow through the entire EGS process. Heat exchange between the reservoir and geofluid is calculated using one of two analytical solutions; the Carslaw and Jaeger (Carslaw and Jaeger, 1959) solution for a single fracture, and the Gringarten (Gringarten et al., 1975) solution for multiple, interacting fractures. The solution method employed is chosen by the user at the start of the simulation. More realistic reservoir scenarios are being developed through a series of dual permeability multi-phase simulations using TOUGH2 (Battistelli, 1997). The results of these simulations will be included in future versions and will be brought into the model using a catalogue of look-up tables. The TOUGH2 reservoir scenarios are developed by varying the permeability ratio and anisotropy in a manner that mimics different fracture patterns and networks in a discretely fractured system.

The current version of the model simulates a single phase system by maintaining a high enough pressure to prevent flashing of the geofluid within the cycle. This is done by calculating the pressure needed to keep the heated geofluid liquid at the inflow point to the power plant and then working backwards to calculate the injection pressure that must be supplied to meet the pressure requirement at the power plant. Pressure loss through the reservoir is based on the Snow estimate for permeability of a fractured medium (Snow, 1968), while the standard Darcy-Weisbach (e.g., Chin, 2000) equation is used to calculate headloss in the pipes. The friction factor for the pipes is calculated using the Jains (Chin, 2000) approximation.

The top-level economics system is simulated using the Geothermal Electricity Technology Evaluation Model (Entingh et al., 2006). Economic parameters such as steel costs, discount rates, etc. that are input into the systems model by the user are transferred to the GETEM, along with the estimated energy production from the plant. The current version of the model uses a static connection meaning that the GETEM is run as a post processing step as opposed to a fully integrated module in the systems model.

Simulation Dynamics

In its current state, the model simulates a binary power plant that is part of an EGS resource. Through a graphical user interface (Figure 4, overleaf), a user is able to create different simulation scenarios. Some of the key, user defined input parameters are listed in Table 1.

![Figure 2. The Tier 1 systems with examples of Tier 2 systems embedded within them.](image)

![Figure 3. Example of a possible progression of Tier functionality for the Tier 1 Well Field system.](image)
The model simulation begins with an initialization period where all time varying parameters are kept constant to calculate the needed injection pressure and for the system to reach steady state. Once initialized, the model forecasts for a period equal to the user defined life-span of the power plant. The user can end the simulation there, or continue beyond the power plant’s life-span for the balance of time up to 50 years. If the production temperature falls below a user defined minimum operating temperature for the plant, then the simulation will pause and issue a warning.

The model has two modes of operation, deterministic and stochastic. The deterministic mode allows a user to create individual scenarios and run them one at a time to see how the system performs for each different scenario. A scenario is defined by a set of input parameters that describes a unique configuration or development plan. In stochastic mode, the user defines a probability density function (PDF) for one or more input variables, and designates one or more output variables to be probabilistically evaluated. Using a Latin hypercube sampling approach, the model systematically steps through the range of input values for any input variable that has been assigned a PDF to produce PDF’s for the set of user-defined output metrics. The stochastic mode is vital for assessing the role and impact of uncertainty in the system.

To illustrate the models functionality, a simple scenario that consists of a 20 MW power plant with a 13\% thermal efficiency that is tapping a 225 °C resource at a depth of 4 km is used (Figure 5). Production and injection wells are fixed to be 3000 m apart. Different scenarios are developed by changing the number of...
injection and production wells; Scenario 1 uses 2 injection wells and 4 production wells, Scenario 2 uses 4 injection wells and 4 production wells, and Scenario 3 uses 2 injection wells and 8 production wells. The diameters of the wells are adjusted for each Scenario to maintain the same total cross-sectional area between each scenario. The simulation runs for a 30 year period.

Figure 6 shows the deterministic results of the change in reservoir temperature and power production over time for each of the three Scenarios. The example shows that there is a clear advantage from a thermal drawdown point of view of using a higher number of smaller diameter producers. Future versions of the model will include real-time economic outputs from GETEM that will provide cost estimates in the evaluation.

Using Scenario 3, a stochastic simulation is run that varies the distance between the injection and production wells using a normal distribution with a mean of 3000 m and a standard deviation of 300 m. Figure 7 shows the variation in production temperature and power production as a function of the distance between the wells. Note that the gap between the 75th and 95th percentile is somewhat smaller than the gap between the 5th and 25th percentile, indicating that the rate of increase in reservoir performance as the distance between the wells is increased is less than the rate of decrease in performance as the wells are brought closer together, implying that some optimal distance must exist. Future versions of the model will add more constraints to the analysis that should help identify the optimal value or probable range of values.

**Summary**

The objective of this project is to develop a model that will assist both DOE and private industry in assessing the physical and economic viability of a geothermal production site. Built on a system dynamics architecture using a multi-tiered modular approach, the model allows a user to perform tradeoff and scenario assessments for a variety of geothermal applications. The tool allows for identifying key areas of uncertainty that if better understood, would provide the largest gain in understanding and predictability and for assessing the set of physical, technological, and economic obstacles that need to be overcome for a geothermal project to become cost competitive.

The tool is being developed with the input and guidance of industry experts, academics, and other DOE researchers and scientists. The initial version of the model was released earlier this year, with future versions to be released as functional plateaus are reached. This allows for transparent development and vetting of the model and its parameters by stakeholders and interested parties who can provide ongoing feedback for improving the tool in the years to come. Due to the variety of users and evaluators, the model also includes a graphical user interface that makes running and using the model relatively easy. In addition to the technical feedback, stakeholders are also asked to comment on the interface and the overall usability of the model.

At its completion, we envision this tool to be a fully integrated computer simulation model that will allow analyses of geothermal energy production over a variety of spatial, temporal, and technological scales.

Future work will focus on further modeling the Tier 1 and Tier 2 functionalities to include:

1. Modeling heat extraction systems beyond EGS
2. Linking to and/or utilizing ongoing work in detailed reservoir modeling
3. Developing the Spatial, Economic, and Institutional modules

4. Continued development of the graphical user interface

5. Soliciting and gathering stakeholder input and involvement

Development beyond the Tier 2 level will be process dependent and will be identified through stakeholder input and the project discovery process.

References


