Models and Risk Management in Geothermal Projects

Roger Henneberger

GeothermEx, Inc., A Schlumberger Company, Richmond, California USA

rhenneberger@slb.com

Keywords: Conceptual models, numerical reservoir models, financial models, risk management

ABSTRACT

Understanding and managing resource risk is a critical factor in making geothermal projects profitable. Objective and robust models of key project elements are important tools for evaluating, reducing and managing risk. Three essential types of models are:

- conceptual hydrogeologic models;
- numerical reservoir models; and
- financial models.

All three models should conform to the basic principles of simplicity, objectivity, plausibility and testability. Adherence to these principles facilitates realistic planning, good decision-making, and agile responses to unexpected results; ignoring them leads to loss of time, money and credibility in the development process. There are potential pitfalls in modeling (mostly related to failure to observe the basic principles) that can lead to an increase rather than a decrease in project risk.

The different models provide critical inputs to the planning, development and operation process, and also provide input and feedback to each other. Therefore, it is important that the models should be consistent with one another, and updated as needed when new information becomes available. Mutual understanding of the purpose, characteristics and limitations of the different models among principal project team members is the best way to ensure consistency.

Reliable and robust models are particularly important at the stage when the developer is seeking project financing, because they serve not only for project planning but also as a vehicle to show potential financiers and their due-diligence consultants that the benefits, costs and risks of the project have been addressed in a systematic way. They are also useful throughout the operating life of a project, for evaluating ways to optimize the exploitation of the resource and thereby maximize the project's profitability.

1. INTRODUCTION

The goal of every commercial geothermal project is to obtain an adequate return (profit) on the investment made in its development and operation. Profitability depends on efficient development and operation, and this in turn requires that the right decisions be made as the project proceeds.

Models of different aspects of a project provide a framework for making the correct decisions, and for evaluating the results of those decisions. Three types of models that are used in most geothermal power-generation projects are:

- A financial model, which represents in a quantitative way the cash flows and economic returns from the project, and incorporates essential information about the exploitation of the geothermal resource.
- A conceptual hydrogeologic model, which describes the geothermal system that is to be exploited for the project, in a qualitative to semi-quantitative way.
- A numerical reservoir model, which quantitatively represents the hydrologic and thermodynamic properties and behavior of the system.

Each model contributes to planning and decision-making in its own way, and, if used together in an effective way, the three types of model provide a system for assessing and managing risk, improving profitability and reducing the chance of failure of a geothermal project. This paper discusses the essential elements of the different models, their interrelationships, and some principles for their effective development and use.

2. MODELING PRINCIPLES

A model is a simplified representation of a real system, which replicates the essential elements of the system so that they can be understood, analyzed and communicated to others. A well-constructed model should have the following characteristics:

- <u>Simplicity</u>: A model should not be more complex than is needed to explain or represent the data and principles on which it is based. As part of this, a model should not contain features that are purely speculative or fundamentally unprovable (that is, there should be some evidence to support each feature included in the model).

- Objectivity: A model should not favor one interpretation over another if the evidence does not support it, nor should it depend on assumptions that are not well supported.

- Plausibility: The features of a model should not violate physical laws (or other applicable principles), should not be excessively optimistic, and should be reasonably inferable from the information available.

- Testability: A model should be designed as a hypothesis whose key elements can be compared against new data, and either confirmed or disproved. As a corollary to this, a model should be updated whenever one of its important elements is contradicted by observations.

Adherence to these principles facilitates realistic planning and agile responses to unexpected results. Ignoring them typically leads to loss of time, money and credibility for the project developer / operator.

3. CONCEPTUAL MODEL

A conceptual hydrogeologic model, in its most fundamental sense, provides a description of a geothermal system that integrates data from different sources, including geologic mapping, geophysical surveys, geochemical analyses and interpretation, and a various data from wells (Figure 1). Most of these data sources are at least partly qualitative, nearly all are subject to uncertainty, and some may contradict each other. Interdisciplinary experience and an objective point of view are needed to construct a conceptual model that meets the criteria listed in the previous section.

The conceptual model should describe the following basic elements of a geothermal system:

- the sources of heat and fluid for the system;

- the location and extent of the geothermal reservoir, in three dimensions;

- the distribution of temperature and pressure in the system;

- the composition of the reservoir fluid;

- the pattern of flow through the system; and

- the geologic features that control the pattern of flow.

None of these elements can be known perfectly, and there may be considerable uncertainty about some of them, particularly in the early stages of a project when few or no wells have been drilled. Nonetheless, the process of describing them (and their associated uncertainty) provides a framework for formulating a hypothesis that can be tested, first against geologic and physical principles, and ultimately against data gathered from drilling and testing wells.

A description of the pattern of flow through the system and the geologic controls on flow represents, in effect, a hypothesis about the nature and distribution of permeability in the geothermal reservoir. This is perhaps the most important component of a conceptual model because it forms the basis for selecting locations and subsurface targets for production and injection wells. It is also one of the most difficult to characterize, because permeability (much more so than temperature) can be distributed irregularly and can vary substantially over small distances. Permeability in most geothermal reservoirs is the result of fracturing (rather than rock porosity), but fracture networks are notoriously difficult to map, even if many wells have been drilled and data have been collected meticulously.

Note that uncertainties in the understanding of the distribution of temperature and permeability translate into uncertainty (and therefore risk) regarding well outcomes. Because of this, if the temperature and permeability uncertainties are understated (or not recognized at all), then there will be an element of development risk that is not properly stated or incorporated in financial projections.

4. NUMERICAL RESERVOIR MODEL

A numerical model of a geothermal reservoir is intended to replicate what can be observed about the reservoir's physical characteristics and behavior, especially from data obtained from wells. As it is commonly implemented, a numerical model represents the reservoir as a network of grid blocks (Figure 2), each of which is assigned a set of hydraulic and thermodynamic properties, which are adjusted as needed to calibrate the model to match observed data. One of several commercially or publically available software packages is used to construct and calibrate the model and generate forecasts with it.

Model calibration is carried out in two stages:

- Initial state (or natural-state) matching, in which the model is calibrated to replicate what is known about the geothermal system in a pre-exploitation state. It is most critical to match the known or inferred distribution of temperature and pressure in the system, because these can be determined with a reasonable degree of reliability.

- History matching, in which the model is calibrated to replicate the response of the reservoir to exploitation (production and injection) during periods of well testing and project operation.

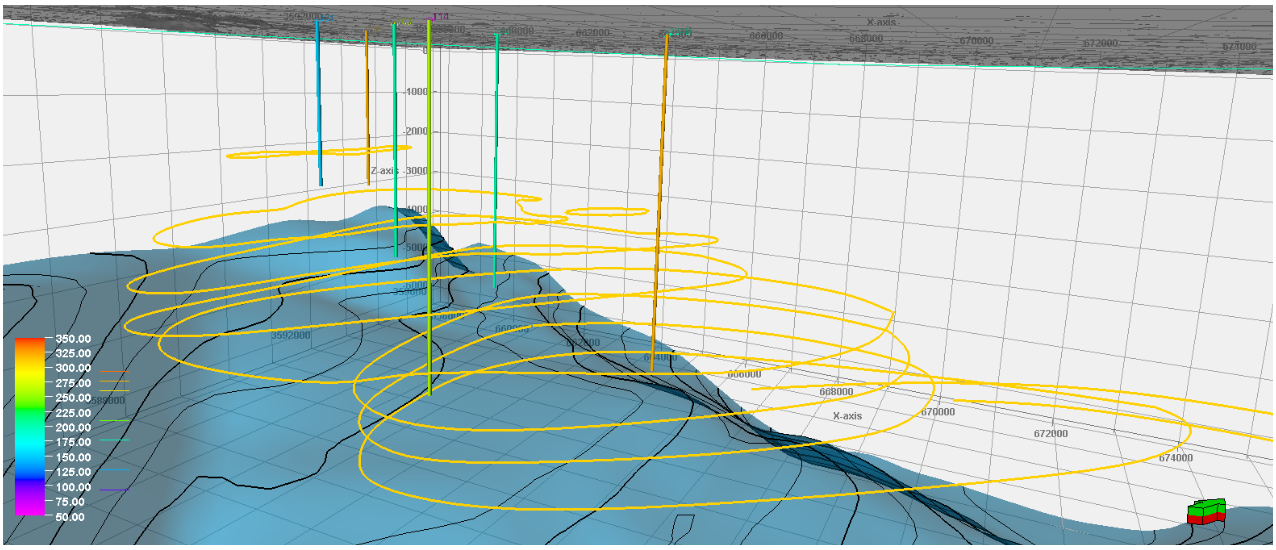

Figure 1: Example of a graphic representation of a conceptual hydrogeologic model, prepared using the Petrel* E&P software platform *Mark of Schlumberger

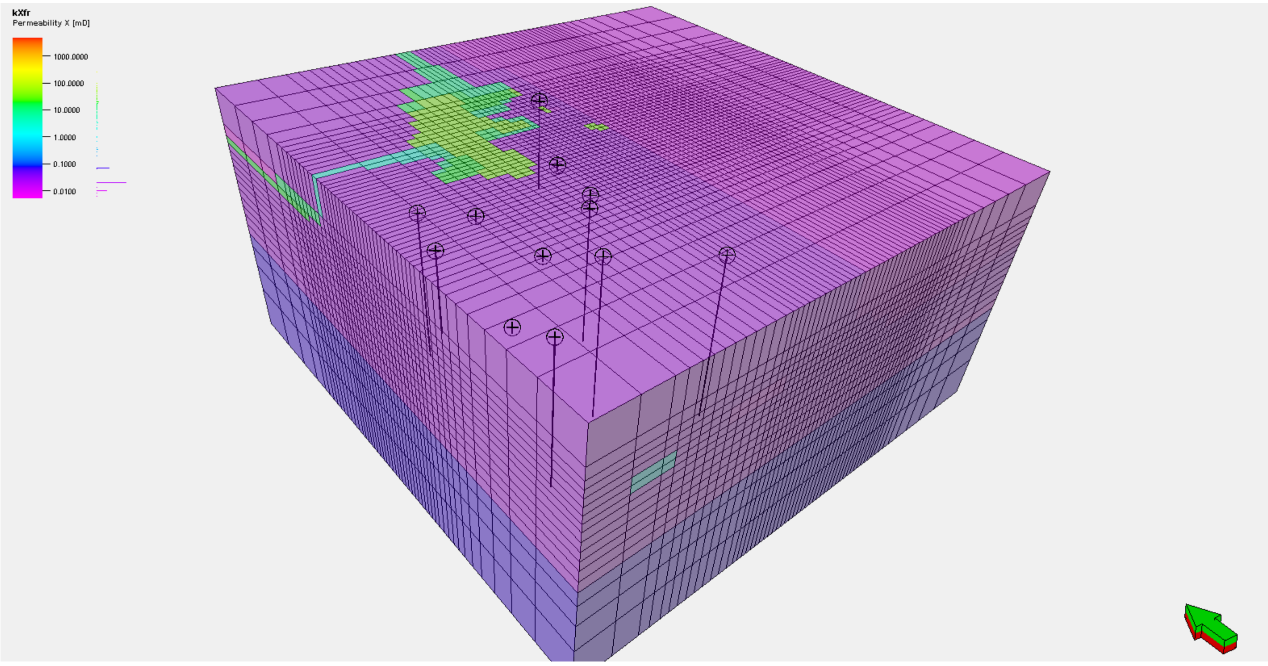

Figure 2: Example of a numerical reservoir model grid

Geologic features, such as particular stratigraphic units and faults, can be incorporated into the model explicitly if their properties (particularly permeability conditions) are well known. However, if their properties are even moderately uncertain, there is a risk that attempting to include such features will bias the model toward an unrealistic representation of the system. In many (if not most) cases it is preferable for the model to be constructed in an unbiased way (not attributing specific properties to inferred geologic features); if this is done, the numerical model may contribute to resolving uncertainties or inconsistencies in the conceptual model on which it is based, instead of being negatively affected by them.

A well-calibrated numerical model can be used to forecast reservoir performance (for example, the trend of reservoir pressure decline) in response to production and injection over periods of time up to and including the expected lifetime of the project (Figure 4). It is therefore an important quantitative tool, though subject to the following limitations:

- A numerical model is non-unique; that is, there is a potentially infinite number of grid configurations that can adequately match the observed data. This means that there is a degree of uncertainty in the model result that cannot be easily quantified.

- The quality of the model improves with the volume of data available for calibration. A model based on a sparse data set (such as results of short-term tests only) will be less reliable than a model based on a long history of operating many wells.

- An inexperienced modeler may construct a model with features (such as zones of excessively high permeability) that are geologically improbable. This makes the model unrealistic, and therefore a poor predictor of real reservoir behavior, even if a match to the data is achieved.

- The model is of limited value for predicting reservoir performance in zones where no data are available (such as undrilled parts of the field).

- The model does not predict the outcomes of individual wells, which depend on conditions that are too localized to be modeled. Therefore, it is not a tool for managing drilling risk (whereas the conceptual model may be, if it is an objective synthesis of the resource data).

5. FINANCIAL MODEL

A financial model (often referred to by other terms such as "cash-flow model" or "pro forma") represents the expected economic performance of a planned or existing project, in terms of the stream of revenue expected over time compared with the costs required to develop and maintain the revenue stream. The form of the model (which is normally developed using a standard commercial spreadsheet software) is not unique to geothermal projects, but there are several important geothermal-specific components or inputs to the model:

- The time required to develop the project, taking into account the requirements of the exploration, development and start-up phases. This schedule is usually implicit in the structure of the model.

- The number and type of wells that need to be drilled to support the project, initially and over the period of project operation. This is translated into a cost schedule for drilling.

- Operation and maintenance costs related to the well field and the geothermal resource. A special category within this group is the cost of well repairs (clean-outs, workovers, etc.) expected over the life of the project. Another is the cost of mitigation of resource-related problems such as scaling or high non-condensable gas levels.

- The level of generation that can be supported by the capacities of the production and injection wells available to the project at any given time. The schedule of generation, and therefore revenue, is developed from this and other parameters (such as plant performance and scheduled maintenance).

- The royalty or other fee (if any) that must be paid for the right to exploit the geothermal resource.

An important point is that these parameters (particularly the number and cost of wells required) can be subject to more uncertainty than is typical in other types of energy or construction projects, especially in the development stage before reservoir conditions are well understood. This represents a source of risk in geothermal projects that is important to characterize as thoroughly as possible; doing so may include developing and analyzing alternative financial models to assess the economic sensitivity of the project to possible variations in key parameters.

6. MODEL INTERRELATIONSHIPS

Figure 4 shows how the different types of models are interrelated in a geothermal project, with one model providing input to another. The figure also serves to illustrate that the different persons or teams working on a project should understand each other's roles and communicate with one another well enough to avoid misapplying the model results. At least one project team member should be familiar with the purpose, characteristics and limitations of all three types of models, to ensure consistency and integration across the project.

The conceptual model supplies critical information about the geothermal resource that is used in both the numerical reservoir model and the financial model. The overall extent of the system and the distribution of temperature and pressure, which are the basis for initial-state calibration, are key inputs to the reservoir model. As mentioned above, elements of the geologic setting may also be incorporated into the reservoir model. Also coming from the conceptual model are the locations of feed zones in the production and injection wells (required for the history-matching process), and the planned distribution and initial capacities of wells (needed to construct exploitation scenarios for making reservoir-performance forecasts).

In the early stages of a project (before a numerical model has been developed), the financial model may depend on the conceptual model for a preliminary indication of the potential project size. The financial model also incorporates the cost of development drilling and surface piping, derived from the depth, design, initial capacities and expected locations of production and injection wells, all determined from the conceptual model. The expected level of expenditures needed to deal with operational issues such as scaling, corrosion or gas is also estimated based on conceptual-model interpretations. Finally, if the conceptual model objectively describes the potential range of uncertainty in its key elements, this can be translated into potential variations in cost and timing that can be used for sensitivity analyses made with the financial model.

The numerical reservoir model provides inputs to the financial model that supplement and, in some cases, supersede those provided by the conceptual model. The numerical model offers the most definitive confirmation of whether the selected power-generation capacity can be supported over the life of the project without excessive resource degradation. Once a final project size has been determined, the numerical model allows for selection of the optimum arrangement of wells (and therefore refinement of the cost estimate for development drilling and surface piping), and the expected decline in well capacities over time, which translates into either reduced generation and revenue, or periodic expenditures to drill make-up wells.

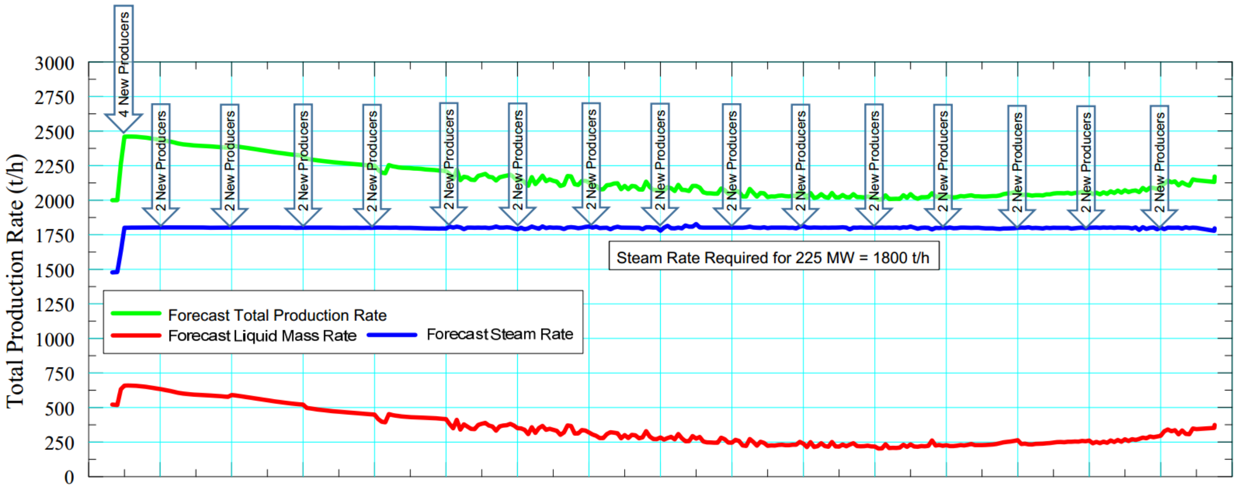

Figure 3: Example of a reservoir performance forecast made with a numerical reservoir model

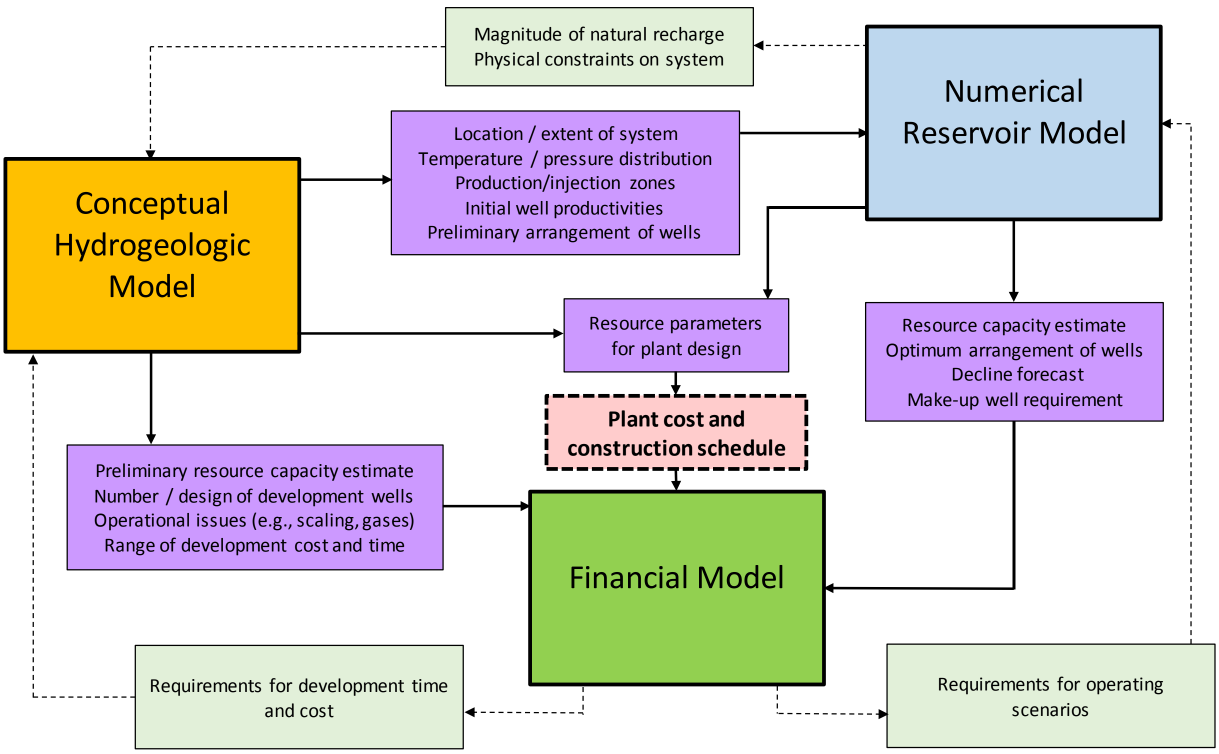

Figure 4: Model interrelationships

Both the conceptual model and the numerical reservoir model yield information that is used to design the power-plant facilities for the project. They therefore indirectly lead to the estimates of cost and timing for plant construction, which have an important impact on overall project economics.

The relationships described above are essentially a "forward" process of one model supplying needed inputs to another, but the models can also provide each other with feedback that helps improve their integrity and reliability. For example:

- The process of developing the numerical reservoir model may identify aspects of the conceptual model that are inconsistent or physically improbable.
- The numerical model can provide an estimate of natural recharge, which may not be available by other means and can be integrated back into the conceptual model.
- The financial model may help to determine the type of operating scenario that is needed to make the project profitable, and therefore guide the design of forecasts to be made using the numerical model.
- Similarly, the financial model may lead to a reexamination of the conceptual model (perhaps looking in more detail at less-explored parts of the field) if there is a need to consider different development scenarios. Care must be taken to avoid loss of objectivity in doing so: for example, there may be pressure to reduce estimates of drilling costs by making unrealistic forecasts of per-well capacity and drilling times, in order to accommodate project economic constraints. If this occurs, it is important to at least acknowledge the additional risk that is being assumed.

7. MODELS AND PROJECT FINANCING

The models discussed here can be used over the span of most or all of the lifetime of a project (Figure 5). The conceptual model, in particular, should be developed in the early exploration stage, and refined and updated during each subsequent stage of the project. Well-developed models take on particular importance, however, at the point where project financing is being sought (typically, the stage where project feasibility can be demonstrated). This is because they provide a vehicle for the developer to show that it has addressed the potential benefits, costs and risks of the project in a systematic way, and to communicate these elements to potential financiers and their consultants who will perform due-diligence evaluations of the project.

The conceptual model should consolidate all available resource data in way that shows clearly what is known (and not known) about the geothermal system. In addition, it should be clear how the conceptual model supports the development plan for the project (especially the number and location of wells to be drilled). Adherence to simple but important conventions, such as keeping a constant scale across different maps and sections (so that data of different types can be compared easily) will help to convey a degree of confidence and clarity in the model. If alternative models have been considered and rejected, they can be described to show that the selected model is the most reasonable and robust.

A well-calibrated numerical model is a powerful tool for demonstrating that the requirements for drilling and the production rate to support power generation over the lifetime of the project have been analyzed and predicted in a quantitative way. Forecasts made under alternative scenarios will help to demonstrate that different approaches have been considered before selecting the one that best balances profitability and risk in the project. As with the conceptual model, a clear and concise presentation of the results will facilitate the review process and show transparency on the part of the developer.

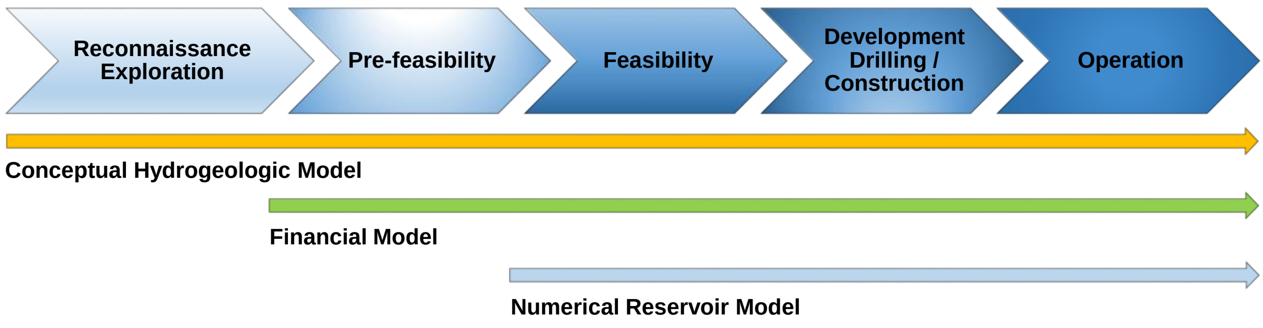

Figure 5: Development and use of models relative to the stages of a geothermal project

A financial model will be required by the financiers, and so it will normally be prepared at this stage, if it has not been already. Because it incorporates cost, timing and revenue projections for all the elements of a project, it distills all of the estimates made from the conceptual and numerical models into a single document, and therefore offers a means to check whether the different models are consistent with one another.

Once again, clarity in the way resource parameters are incorporated and presented in the model will facilitate review. For example, it should be clear how revenue is calculated from the generation level, how generation is calculated from the available supply of fluid, how the fluid supply is calculated for the number of available wells, and how the number of wells is determined from parameters supplied by the conceptual and numerical reservoir models. If any of the derived quantities are "hard coded" instead of calculated, it raises questions about whether assumptions that are inconsistent with the conceptual or numerical model may have been used.

8. MODELS AND PROJECT MANAGEMENT

Once a project begins operation, its profitability depends on maintaining generation at as high a level as possible, while controlling costs (including expenditures for new wells and for remediation of resource-related problems). The judicious use of the conceptual, numerical and financial models can play a central role in this effort.

The conceptual model continues to serve as the basis for selecting locations and targets for any new wells that may be required. It is therefore important that the model continue to be updated through the period of project operation. At this stage, the conceptual model can also be used to estimate the probability of drilling success, and therefore to help evaluate whether it will be more cost-effective on a risk-weighted basis to drill new wells to maintain production, or instead to allow the generation level to fall as well outputs decline. The model may also play a part in understanding changes in the behavior of the system and the wells over time (for example, changes in gas concentrations or other chemical characteristics of the fluids produced).

The numerical reservoir model can be used as an overall tool for assessing and, if necessary, adjusting the strategy for field exploitation, especially as regards the possible relocation of injection to optimize production-well performance. It can also play a part in assessing the cost-effectiveness of make-up drilling, by predicting the effect of new wells on the existing production wells and the overall rate of production decline. Finally, the model is the essential tool for evaluating whether the project may expanded successfully without placing too much stress on the reservoir, and thereby provoking excessive rates of decline. Note that comprehensive and accurate monitoring of reservoir conditions (for example, through instrumentation of idle wells for pressure monitoring, routine sampling and analysis of produced fluids, and periodic chemical tracer tests) is necessary to make the reservoir model as useful as possible through periodic recalibration against high-quality data.

The financial model can be used in conjunction with the conceptual and numerical models to assess the economic impacts of operational changes that are being considered. As an example, the effect on cash flow of a decision to drill multiple make-up wells in a single drilling campaign (saving the cost of one or more rig mobilizations, but possibly securing some production capacity that cannot be used immediately), instead of deferring one or more wells until later, can be evaluated using the financial model. This decision has little or no technical impact on the project, but its economic impact may be significant. Communication between the different parts of the project team remains important in providing the information needed to properly assess the costs, timing and risks associated with different project-management options.

9. PITFALLS IN MODELING

Like any tools, models are effective when used properly, but may cause problems when they are not. Most problems related to modeling are the result of a failure to adhere to the principles listed above. Some common examples are discussed here.

9.1 Excessive Complexity

Developing or presenting a model in a way that is so complex that others cannot readily understand its underlying assumptions and conclusions creates a risk that the model results will be misused. While some complexity may be needed in specific situations, it should be possible to explain the basic elements of a model in such a way that a non-specialist can understand them. Unnecessarily complex models are also more likely to contain features that are not substantiated by observational data; this increases rather than reduces risk.

9.2 Ignoring Conflicting Data

Rejecting or overlooking a part of the available data so that the model can yield a preferred or preconceived result reduces the validity of the model. Even if there is a conflict in the data that forces a choice to be made between competing models, the conflict should be mentioned, and expressed as an uncertainty in the model (which can be checked and perhaps resolved in the future when more data become available).

9.3 Failure to Acknowledge Uncertainty

Understating or not acknowledging the uncertainty in a model gives an incorrect representation of the level of resource risk that is present at any given stage of the project. This can be a particular problem when the model results are presented graphically (as maps or cross sections) or numerically, because this type of presentation conveys a sense of accuracy and certainty that may not be justified.

9.4 Failure to Question Model Assumptions

If new data show that a model prediction was inaccurate, the assumptions on which the model is based should be re-examined, rather than simply adjusting parameters to fit the new data. An example that occurs frequently is the failure of a well to encounter permeability where a fault plane is projected. Too often, the response is to simply redraw the fault location(s) to account for the failure (and proceed to select new drilling targets in the same way as before), without addressing the questions of:

- Is there strong evidence that permeability is uniquely or preferentially associated with identifiable faults (rather than a more dispersed and random fracture network)?
- Can the faults be identified and located with enough accuracy to justify their being selected as well targets?
- Have other hypotheses about the nature of reservoir permeability been adequately considered?

An effective approach is to treat each new data-collection task (especially each new well) as a test of the model, with ideas in place beforehand as to what result will constitute a confirmation of the model, and how the model will need to be adjusted if the confirmation is not achieved.

10. FINAL POINTS

Everyone on the team of a commercial geothermal project is participating in an effort whose results can be measured in terms of profit or loss. This implies an obligation for everyone to make the best use of resource data and other data (and to acknowledge when there are uncertainties), to organize information well, and to communicate effectively across varying specialties so that decisions can be made in a way that manages risk and provides the best chance of good results. Establishing and maintaining robust and reliable models provides a framework for addressing all of these objectives.

Over the past few years, there has been a widespread emphasis in the geothermal industry on the analysis and mitigation of risk in geothermal power-generation projects, with a focus on external mechanisms for mitigating risk to help facilitate more development. This focus is valid, given the risks that are unique to geothermal development, but it should not displace efforts to manage and reduce risk internally. Verifying that valid models are in place is a simple and quick way to determine whether a project and its team have a serious and disciplined approach to managing risk.