USING SYSTEM DYNAMICS FOR UNCERTAINTY ANALYSIS AND INTEGRATED RISK ASSESSMENT IN GEOTHERMAL ENERGY DEVELOPMENT

Thomas S. Lowry, Elena Kalinina, Teklu Hadgu, Sean A. McKenna

Sandia National Laboratories
P.O. Box 5800 MS1137
Albuquerque, NM, 87059, USA
e-mail: tslowry@sandia.gov

ABSTRACT

The objective of this study is to use system dynamics (SD) modeling to aid in the development and management of geothermal energy production by placing uncertainties in knowledge and understanding into a risk-based framework. Here, we focus on the development of the SD model, GT-Mod, and its use in performing uncertainty analysis and integrated risk assessment. Built within the Powersim development environment, GT-Mod simulates the economic and thermal performance of a given geothermal energy site to calculate the levelized cost of electricity (LCOE) as a function of known and unknown (i.e., uncertain) physical and economic conditions. GT-Mod uses a Monte-Carlo approach to propagate uncertainties in a variety of economic and physical descriptor parameters to estimate the integrated risk of achieving a target LCOE. Integrated risk assessment is an approach that focuses on the uncertainties in knowledge and understanding that cause uncertainty in the predicted future and is calculated as the sum of the consequence, C, multiplied by the range of the probability, ΔP, over all estimations of a given exceedance probability, n, over time, t. GT-Mod can be used by engineers, project planners, potential investors, etc. to identify the optimal solution space for a given set of site characteristics, and power plant and well configurations. The tool identifies the key areas of uncertainty that if better understood, would provide the largest gain in understanding and predictability and hence, the largest reduction in risk. Furthermore, the tool is able to identify and assess the set of physical, technological, and economic hurdles that are preventing a geothermal project from becoming market competitive.

The analysis assumes a realistic but fictitious enhanced geothermal system (EGS) site with uncertainties in the exploration success rate, the sub-surface thermal gradient, the reservoir permeability, and the power plant performance. Economic uncertainties include uncertainty in the cost of exploration, construction, O&M, and drilling. GT-Mod propagates input uncertainties by describing them with probability density functions (PDF's) and then simultaneously varying the PDF's via a Latin Hypercube Sampling (LHS) technique across multiple runs. Exceedance probabilities for the LCOE are then calculated as a post-processing exercise. Results show that the LCOE assumes a lognormal distribution with the tail skewed towards the higher values and a mean LCOE that is almost 25% higher than the best estimate, which is based on the mean values of the input PDF's. Correlation analysis indicates that reductions in drilling costs and better characterization of the sub-surface environment will reduce risk the most.

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. The full suite of systems and sub-systems result in a set of multi-tiered dependency structures with multiple feedback loops that propagate uncertainties in the inputs in non-linear and unintuitive ways. Understanding the propagation of these uncertainties in the context of economic risk of development is paramount if geothermal energy production is to become cost competitive.

This study uses an example enhanced geothermal system (EGS) and the uncertainties associated with developing an EGS site to illustrate the approach. EGS is an approach for accessing thermal energy from the earth that involves drilling deep (2-10km) boreholes into hot, geologic material (usually crystalline rock) and extracting heat by first fracturing the rock, and then circulating a working fluid (usually water or CO_2) through the system. Estimates show that within the Continental United States alone, access to only 2% of the heat from 3 to 10 km deep could meet 2,500 times the United States' current total energy use (MIT 2006). This type of potential is equally valid for most parts of the world. However, while the potential of EGS is enormous, uncertainties in the cost of development, thermal performance, and operational reliability have hindered its development. Complicating this situation is the fact that these uncertainties are dependent variables, meaning that they can exist in dynamic relationship with other processes and uncertainties.

This work is employing system dynamics in developing an integrated modeling tool called GT-Mod (Lowry et al. 2010) that dynamically links the various connected yet disparate systems of a geothermal problem to simulate the collective performance of the systems over time. Built within the Powersim development environment, GT-Mod represents each of the individual systems of a geothermal energy project as individual systems that communicate with each other using dynamic linkages of mass and/or energy. The four primary systems in the model are the power plant, the geothermal reservoir, the injection wells, and the production wells, with each of the primary systems composed of one or more sub-systems. The conceptual structure of GT-Mod is shown in Figure 1.

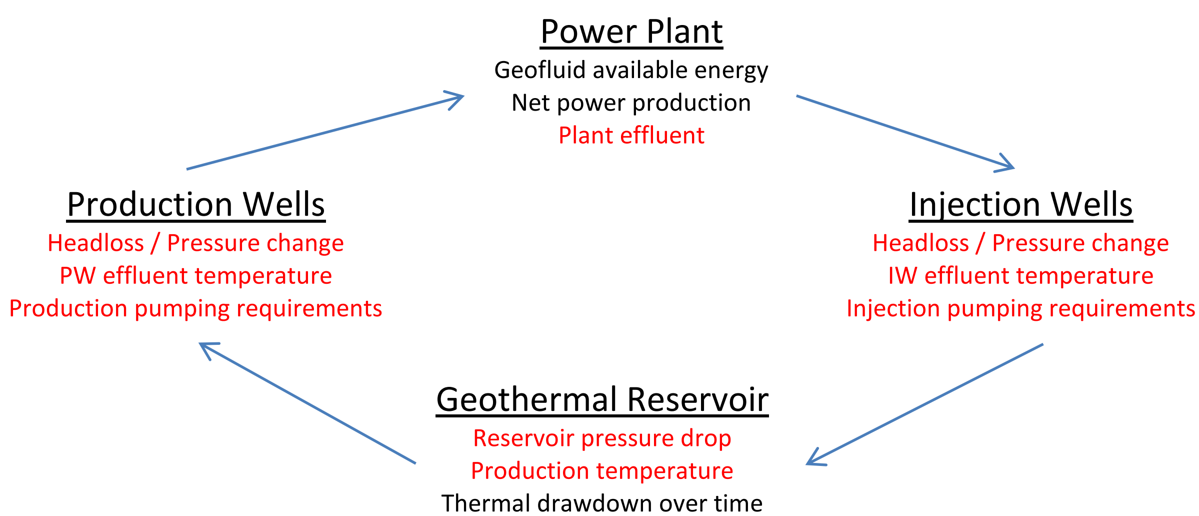

Figure 1 - Conceptual layout of GT-Mod showing the four main systems and their primary sub-systems. Items in red indicate calculations that are linked to systems or sub-systems outside its own.

GT-Mod simulates the time varying pressure regime, thermal drawdown, plant performance, and economics as a single, system of systems. Economic analysis is accomplished through a real-time, two way connection to a modified version of the Geothermal Energy Technology Evaluation Model (GETEM) (Entingh et al. 2006) that calculates the levelized cost of electricity based on time-series performance output from GT-Mod.

GT-Mod allows a user to define a probability distribution function (PDF) for any number of input variables. The inputs can be defined using uniform, normal, log-normal, truncated normal, exponential, or triangular distributions. GT-Mod uses a Monte Carlo approach to propagate the input uncertainties by varying each of the PDF's across its range of values via a Latin Hypercube Sampling (LHS) technique. Output from the model is collected and processed to produce a cumulative probability function of the LCOE (or any output metric) and to calculate the integrated risk as a function of the input uncertainty.

INTEGRATED RISK

Generally, uncertainty manifests in both the inputs and the outputs of an analysis. For the inputs, uncertainty reflects the confidence that the value of an input is the 'true' value for the analysis in question. Uncertainty in the outputs result from the propagation of input uncertainties, the assumptions used to create the simulation algorithms, and numerical inaccuracies in the solution method. The integrated risk assessment in GT-Mod is similar to that used by the insurance industry to assess their exposure to loss and can be thought of as a means to quantify the influence of uncertainties in the inputs on the range of outputs.

Integrated risk assessment relies knowing the consequence(s) of an event (or set of events) as well as the probability of that event occurring. To quantify risk, we utilize the approach introduced by Helton (Helton 1994) who defines risk as the sum of the consequence, C, multiplied by the range of the probability, ΔP, over all estimations of a given exceedance probability, n, over time, t:

$$R = \sum_{t}\sum_{n} C(n,t)\Delta P(n) \tag{1}$$

The risk calculated with equation (1) represents the sum of the risk for all events across all probabilities. For our purposes, an 'event', or scenario, is the model output that results from a single combination of input parameters. Integrated risk provides a metric to quantitatively compare different scenarios and to assess the tradeoffs between lower-probability higher-reward scenarios versus higher-probability lower-reward scenarios.

EXAMPLE PROBLEM

To illustrate the capabilities of GT-Mod, we use a fictitious EGS site that is configured to produce 30 MWe at the start of the simulation. Configuring the site is done automatically in GT-Mod and involves setting the number of injection and production wells, the total mass flow rate of the working fluid through the plant, well design parameters such as borehole diameters and casing lengths, and injection and production pump depths and rates (if needed). The mass flow rate is kept constant throughout the simulation, which means that electricity production drops over time as a consequence of the declining production temperature and efficiencies. Example outputs showing the reduction in the production temperature and power generation over time are shown in Figure 2.

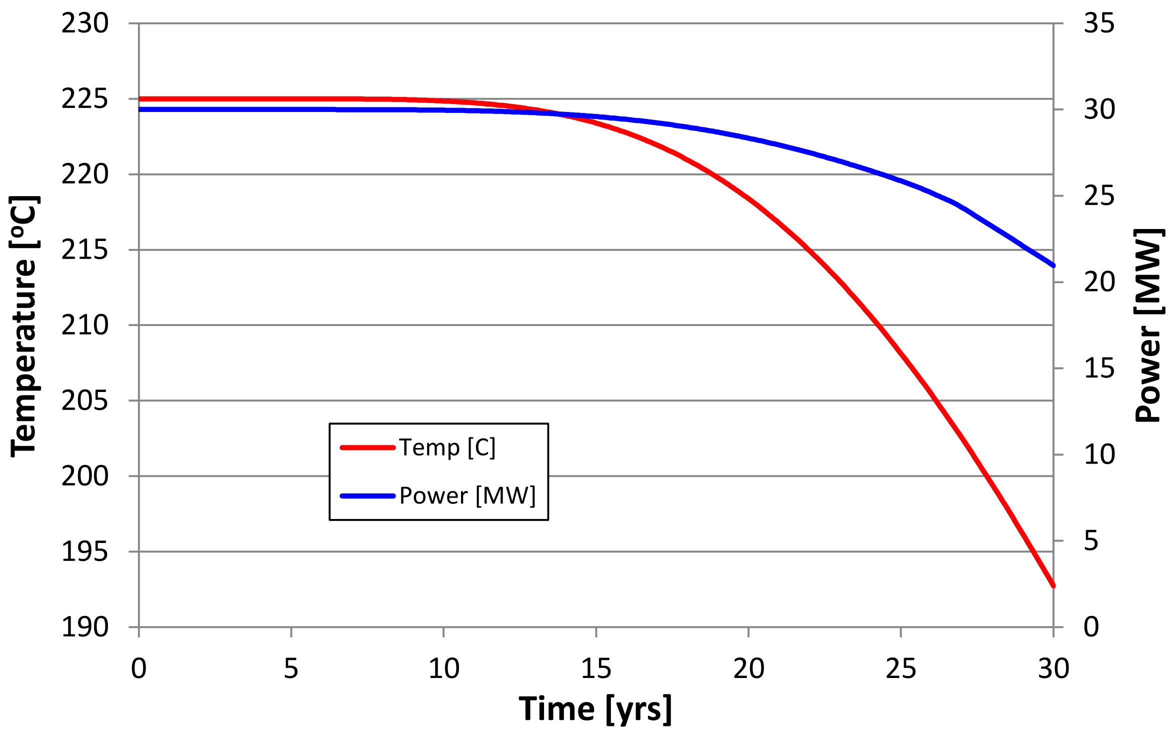

Figure 2 - Example output from GT-Mod showing the time variation in production temperature and power production.

The uncertainty analysis focuses on the costs of drilling as well as the costs of raw material and labor. Drilling costs are a function of the depth of the resource, the penetration rate of drilling, equipment reliability, the cost of steel and cement, and the drill-rig labor rates. To introduce uncertainty in these inputs, multipliers are used to vary the input about a default value. Other cost uncertainties are introduced by adjusting the utilization factor (the percent of time the plant is operating), a multiplier on the total plant cost, and the percent of indirect costs associated with building and operating the plant. In all, eleven parameters are defined as uncertain and are listed in Table 1 below.

As the thermal gradient is varied, the resource depth is adjusted to match the 225 ^{o}C target resource temperature. As mentioned above, the number of wells for each simulation is based on the 30 MWe power output, and the brine effectiveness, which is calculated using a regression against the design temperature. Variations in the mass flow rate, the number of fractures, and the fracture aperture impact the hydraulic drawdown and thermal performance of the reservoir. In turn, the hydraulic drawdown and depth of the resource influences whether or not pumping is needed and whether it is on the injection side, the production side, or both. Within GT-Mod, the Gringarten (Gringarten et al. 1975) analytical solution option was chosen to calculate the thermal drawdown and the Snow estimation (Snow 1968) was chosen to calculate the pressure drop through the reservoir. All other sub-surface parameters are kept constant, as are parameters describing the economics, operations, and maintenance costs.

Table 1 - List of variable input parameters, their default values, and their distribution functions.

Name	Description	Default Value	Distribution Type	Distribution Parameters
Utilization Factor	% time plant is operating	95%	Triangular	Min: 85.0% Peak: 95.0% Max: 98.0%
Power Plant Cost Multiplier	Adjusts turbine generator, condenser, heat exchanger, and working fluid pump costs	\$398.65 / kW, \$204.32 / kW, \$50.21 / kW, \$36.32 / kW	Uniform	0.80 – 1.20
Percent Indirect Costs	% of plant cost to calculate indirect costs	8%	Triangular	Min: 5.0% Peak: 8.0% Max: 12.5%
Casing Cost Multiplier	Material costs of casing	\$2.01 / lb	Uniform	0.80 – 1.20
Cement Cost Multiplier	Material costs of cement	\$175.00 / ft^3	Uniform	0.80 – 1.20
Fracture Aperture	Effective fracture aperture	1 mm	Uniform	0.25 – 3.00 mm
Subsurface Water Loss	% water loss that must be replaced	5%	Triangular	Min: 2.0% Peak: 5.0% Max: 10.0%
Trouble Index Multiplier	Adjusts estimated drilling and casing time	1.0	Uniform	0.80 – 1.20
Penetration Rate Multiplier	Adjusts drilling penetration rate	30 ft/hr < 10k ft 15 ft/hr > 10k ft	Uniform	0.80 – 1.20
Bit Life Multiplier	Adjusts life of drilling bit	100 hrs	Uniform	0.80 – 1.20
Thermal Gradient	Adjusts thermal gradient	43.87 °C/km	Normal	μ = 43.87 °C/km σ = 9.9 °C/km

RESULTS

The comparisons are made on the net revenue generated over the 30 year lifetime of the plant using the following equation:

$$R_{tot} - C = R_{net} \tag{2}$$

where R_{tot} [\$] is the total revenue and C [\$] is the total cost. The total revenue is calculated using:

$$S_e P_c T U = R_{tot} \tag{3}$$

where S_e is the effective sale price of electricity [¢/kW-hr], P_c is the production capacity of the power plant, T is the lifetime of the power plant, and U is the utilization factor. The costs, C, for each scenario are also calculated using equation (3) by substituting the calculated LCOE for the effective sale price, S_e. The effective sales price of 9.829 ¢/kW-hr is based on data from the US Energy Information Administration (US Energy Information Administration 2011) and was derived as a weighted average of the monthly sales price of electricity from all sources for the residential, commercial, industrial, and transportation sectors for 2009 and 2010. The net revenue for the default case, D_{net}, is \$166.0 million dollars over 30 years (D_{net} assumes an LCOE of 8.5 ¢/kW-hr and a utilization factor of 95%).

Figure 3 shows the results for the LCOE as a cumulative distribution function (CDF) that describes the probability that the LCOE will be below a given value. It is interesting to note that there is only a 32.1% chance that the LCOE will be less than or equal to the default LCOE value of 8.5 ¢/kW-hr, despite the fact that the default values for the variable inputs lie either at the center or the peak of their respective PDF's. While the default case is deemed the most probable from a parameter estimation point of view, the distribution of the LCOE is not necessarily symmetrical about that value. In this case, the results are skewed towards a higher LCOE than the default would indicate.

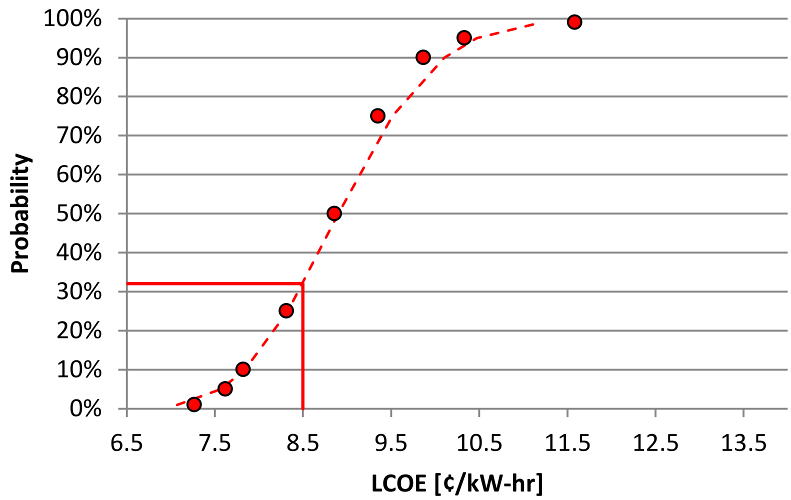

Figure 3 - Cumulative distribution function of the LCOE. The CDF shows the probability that the LCOE will be less than a given value. The solid red line indicates the LCOE (8.5 ¢/kW-hr) and probability (32.1%) of the default case.

Figure 4 shows a complimentary cumulative distribution (CCDF) plot of the net revenue, R_{net}, as well as the difference between R_{net} and D_{net}. A CCDF plot describes the probability that the 'real' scenario will be greater than the value at that probability. The plot shows that the probability of producing positive revenue is about 89% (solid blue line). Conversely, the probability of exceeding the default performance is only 31.2%, which means that if projections are based solely on the default input values, there is a 2 out of 3 chance that the actual performance will fall below that number.

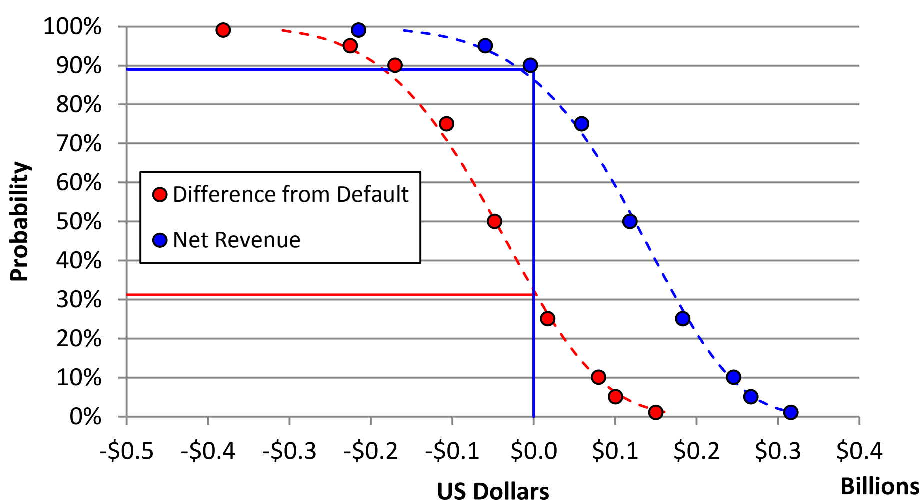

Figure 4 - Complimentary CDF for net revenue and the difference between net revenue and the default case. The solid red and blue lines indicate the probabilities associated with the 'break even' point of each distribution (31.2% for net revenue, 89.0% for the difference).

The calculated risk for the difference between R_{net} and D_{net} is about $72.0 million (Figure 5). The risk is calculated using equation (1) and assumes that the risk is zero for scenarios where R_{net} is greater than

D_{net} and in this case, represents a loss as compared to the default scenario. The figure shows the cumulative risk plotted over the R_{net} - D_{net} CCDF, with the axes rotated so that probability is now on the x-axis, and dollars are on the y-axis. The risk is not a probability function meaning that the final value of $72.0 million is integrated across all revenues and all probabilities. The difference between D_{net} and the risk is about $94.0 million, which now becomes the probabilistically weighted estimate of R_{net} and which corresponds to an effective LCOE of 9.1 ¢/kW-hr. From a risk-based decision making point of view, the decision maker must now decide if the potential gains are worth the risk.

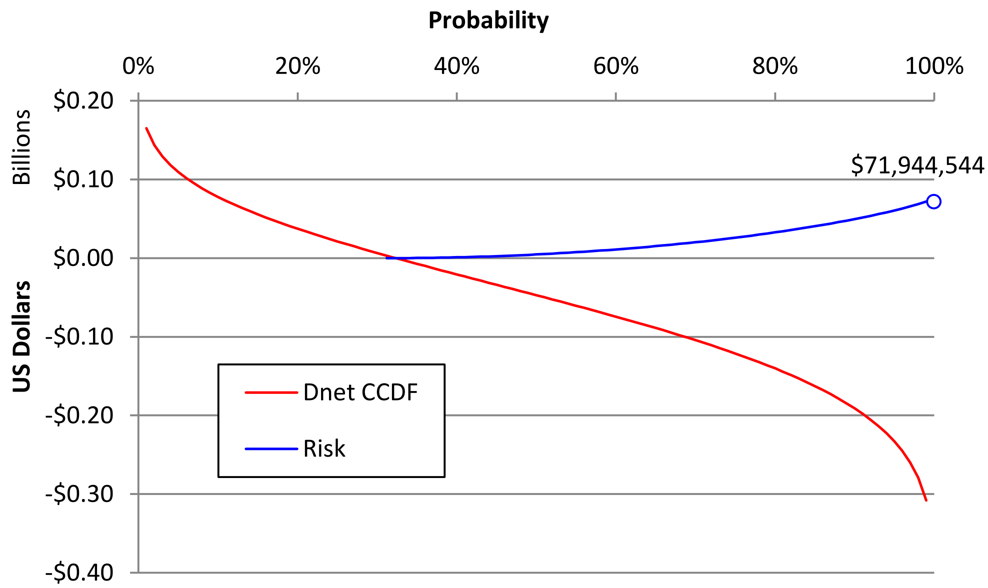

Figure 5 - The CCDF for the difference in net revenue, D_{net}, and the integrated risk. The total risk for this example is $71,944,544.

Correlation analysis is used to determine which inputs contribute the most to the variability in the LCOE estimates (Table 2) and is useful for deciding on where to place future efforts to reduce uncertainty (i.e., risk) the most. In this case, changes in the trouble index, the penetration rate multiplier, and the thermal gradient influence the value of the LCOE the most. Since the thermal gradient sets the depth of the resource, it is clear that factors concerning the drilling time are important to the LCOE and if one desires to reduce the LCOE, effort should be placed on reducing the drilling time. Conversely, if reducing the drilling time is not feasible, reducing the uncertainty in the estimations of the drilling time will provide more certainty to the LCOE predictions and reduce the risk of incorrectly assessing the site. The next most influential inputs are the indirect costs followed by the casing material costs. It should be noted that the correlations can be highly influenced by the PDF and more importantly, the spread of potential values for each input and that when risk analysis of this type is used in the real world, care should be given when forming the PDF's.

Table 2 - Correlation coefficients for each of the variable inputs against the LCOE.

Variable Name	Correlation with LCOE
Utilization Factor	0.011
Fracture Aperture	-0.010
Subsurface Water Loss Percentage	0.001
PP Cost Adjustments	-0.044
Indirect Cost Percentage	-0.061
Trouble Index	-0.192
Penetration Rate Multiplier	0.156
Bit Life Multiplier	0.007
Casing Cost Multiplier	-0.052
Cement Cost Multiplier	0.039
Thermal Gradient	-0.123

SUMMARY

Most of our understanding of a geothermal resource is obtained from indirect measurement and or inference and even for cases where the knowledge is high, uncertainty remains. Models used to assess the resource rely on this understanding to populate their inputs such that they reflect the effective characteristics at the site. Due to model sensitivity, some inputs require high precision while others are less stringent. Historically, when simulating thermal or economic performance, uncertainty has typically been addressed by assuming a mean value for each of the inputs, and then perturbing the values about that mean to try and bound the range of possible answers. That range is then reported as a mean prediction plus or minus the variability about that mean.

In this study, we utilize system dynamics to link together the myriad of physical and economic systems that comprise a geothermal energy assessment in order to address uncertainty. Called GT-Mod, the model provides an integrated risk framework that aids decision and policy makers by providing a single metric (integrated risk) to compare between scenarios. The approach propagates uncertainty in model inputs using a Monte Carlo / Latin Hypercube Sampling approach to produce probabilistic output. The example presented above is based on a consequence metric defined as the difference of the simulated net revenue and a target value. The risk is calculated as the summation over all scenarios (i.e, over all combinations of parameter inputs) of the product of the revenue deviation and its probability and quantitatively describes the consequence of the gaps in knowledge and understanding of the site. Integrated risk assessment provides a decision maker with a higher degree of insight regarding the consequence of his or her decision while simultaneously identifying the areas where better understanding would most help the decision making process.

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