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

or: Can Physics and Analysis Live Together?

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1. INTRODUCTION

Geothermal Energy (GTE) Development requires knowing and understanding the fundamental systems of:

1. Heat Extraction (Reservoir Performance)
2. Heat Conversion (Plant Performance)
3. Well Field (Physical Operations)
4. Spatial Constraints (Geographic Limitations)
5. Economics
6. Institutional Constraints

Failure to adequately understand of any of these systems and the relationships between these systems results in higher uncertainty, lower investment rates, longer development times, and reduced market penetration.

A gap exists between the physical and non-physical aspects of GTE development (FIGURE 1).

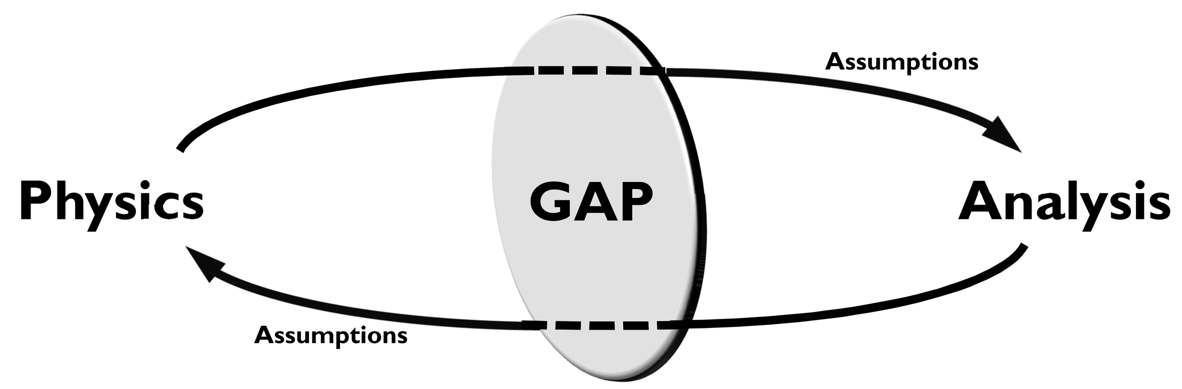


FIGURE 1 – This work bridges the gap between the physical and non-physical aspects of GTE development.

2. OBJECTIVE

This work is filling the gap between the physics and analysis by creating an integrated systems model that accounts for the inter-relationships and feedbacks between each of the six systems described above. The model captures the dynamic and temporal relationships that cause the non-linear and un-intuitive behavior that are difficult to assess.

3. METHODOLOGY

The approach is conceptualized as a multi-tiered system of systems where the upper most Tier is made up of the six fundamental systems. Each system is dynamically linked where appropriate to the next. For instance, the heat extraction and heat conversion calculations are mutually dependent (FIGURE 2).

Successive Tiers provide ever increasing detail to the upper Tier systems.

The model is designed to leverage research and analysis on an ongoing basis to include new understanding in the model as it becomes available.

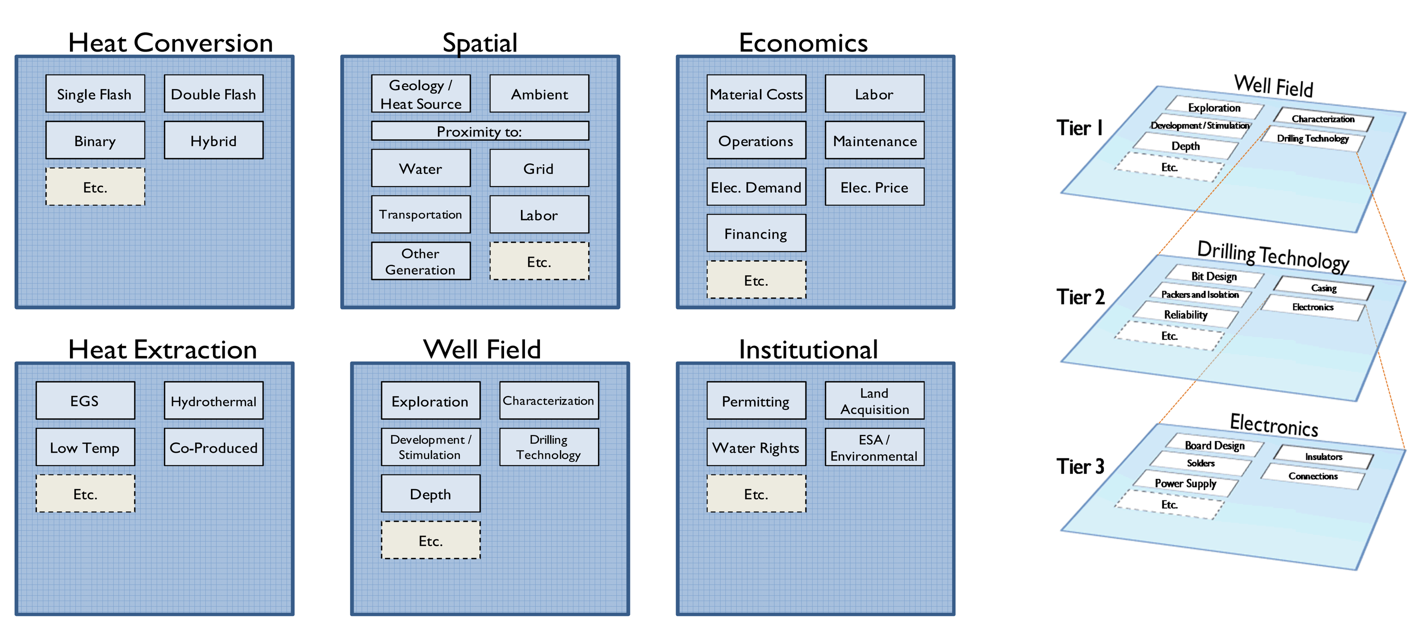


FIGURE 2 – Each Tier is composed of a set of sub-Tiers (left) with each successive sub-Tier providing increasing detail.

4. IMPLEMENTATION

The project consists of two parallel efforts:

1. Design and creation of the multi-tiered systems model
2. Stochastic simulation of reservoir performance

4a. DESIGN AND CREATION OF THE MULTI-TIERED SYSTEMS MODEL

The current model simulates heat and fluid flow, pressure and parasitic losses, and net power production for a binary power plant at an EGS site (FIGURE 3). 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. More complex solutions methods will be added to the model in later versions

A user interface allows the user to quickly change input values and to view output in real-time (FIGURES 4 & 5).

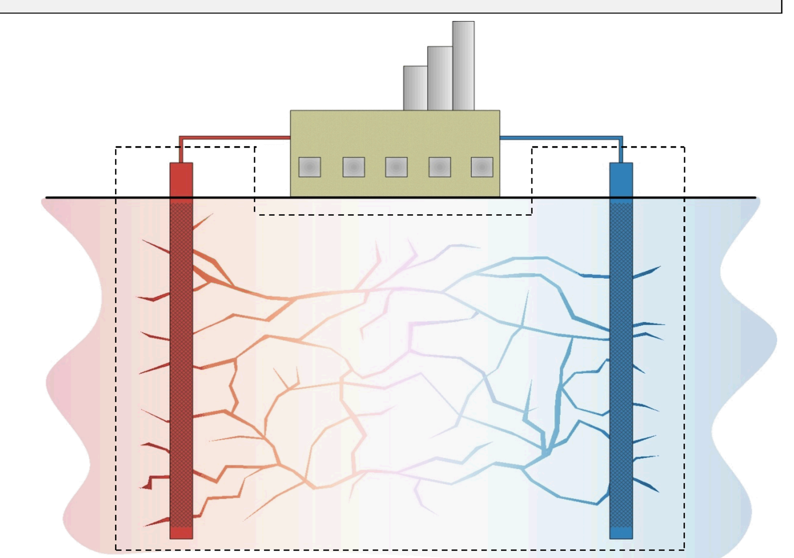


FIGURE 4 – The current model simulates an EGS from the exit point of the power plant to the entry point, treating the power plant as a 'black-box'. Several analytical solutions are available to simulate reservoir performance but the model maintains the ability to include more detailed simulations.

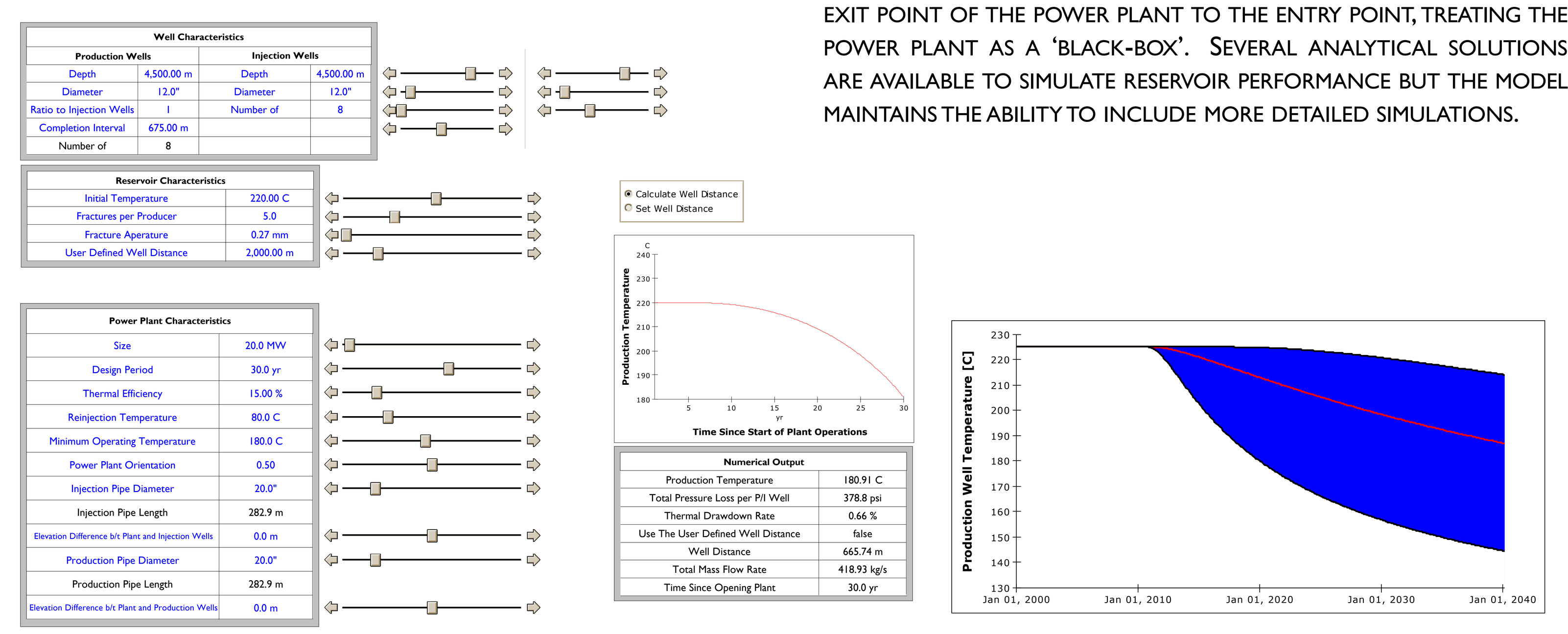
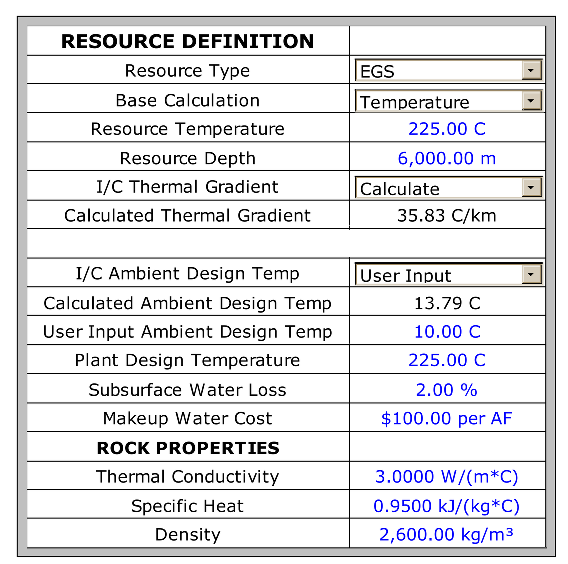


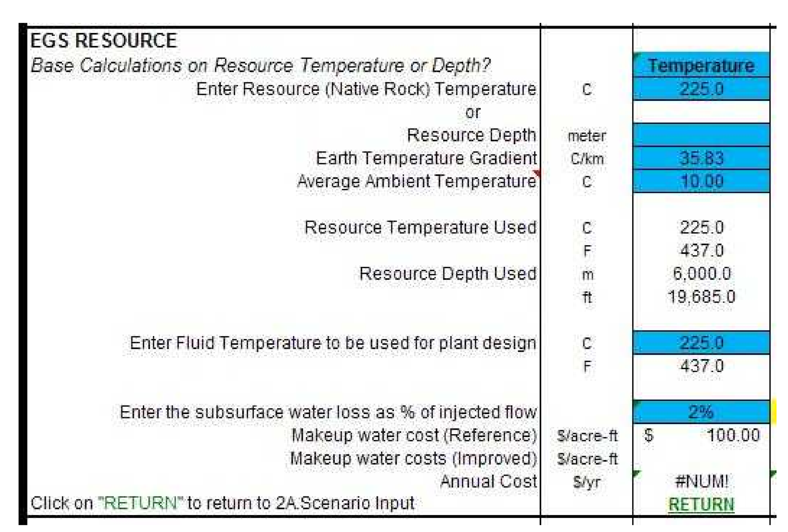
FIGURE 5 – Screen shot of the user interface and selected output graphics. The right-most figure illustrates the output from a risk-based assessment of temperature decline as a function of distance between the injection and production wells. The range shows the 5-95 percentiles.

The model is linked to the 'Geothermal Electricity Technology Evaluation Model' (Entingh et al., 2006) that is used to perform the economic analysis piece of the evaluation. A separate interface (FIGURE 6) provides a means for the user to input GETEM specific variables. Where GETEM needs a static input to a dynamic process (e.g. thermal drawdown rate), the model calculates an effective value at the end of the simulation that gets passed into GETEM.



RESOURCE DEFINITION	
Resource Type	EGS
Base Calculation	Temperature
Resource Temperature	225.00 C
Resource Depth	6,000.00 m
I/C Thermal Gradient	Calculate
Calculated Thermal Gradient	35.83 C/km
I/C Ambient Design Temp	User Input
Calculated Ambient Design Temp	13.79 C
User Input Ambient Design Temp	10.00 C
Plant Design Temperature	225.00 C
Subsurface Water Loss	2.00 %
Makeup Water Cost	$100.00 per AF
ROCK PROPERTIES	
Thermal Conductivity	3.0000 W/(m*C)
Specific Heat	0.9500 kJ/(kg*C)
Density	2,600.00 kg/m³

The systems model input interface includes all the inputs to GETEM, which are mapped directly into GETEM.



EGS RESOURCE		
Base Calculations on Resource Temperature or Depth?		Temperature
Enter Resource (Native Rock) Temperature	C	225.0
or		
Resource Depth	meter	
Earth Temperature Gradient	C/km	35.83
Average Ambient Temperature	C	10.00
Resource Temperature Used	C	225.0
	F	437.0
Resource Depth Used	m	6,000.0
	ft	19,685.0
Enter Fluid Temperature to be used for plant design	C	225.0
	F	437.0
Enter the subsurface water loss as % of injected flow		2%
Makeup water cost (Reference)	$/acre-ft	$ 100.00
Makeup water costs (Improved)	$/acre-ft	
Annual Cost	$/yr	#NUM!
Click on "RETURN" to return to 2A.Scenario Input		RETURN

FIGURE 6 – Screen shot of a piece of the GETEM input page from the model (left) and the corresponding entry cells to GETEM (right). Calculated values such as thermal drawdown rates or pumping requirements are calculated as effective values at the end of the systems model simulation. The entire range of inputs to GETEM can be entered through the systems model interface.

4b. STOCHASTIC SIMULATION OF RESERVOIR PERFORMANCE

More realistic reservoir performance scenarios are being developed as part of this project through a series of dual permeability multi-phase simulations using TOUGH2 (Battistelli, 1997). The simulations are using a geo-statistical approach to generate ensembles of permeability fields across a range of fracture properties, fracture and well configurations, power plant efficiencies, and flow rates (FIGURE 7). Simulations of the production temperature over time will be aggregated to a set of look-up tables for use in the systems model. These results will be included in future versions of the model.

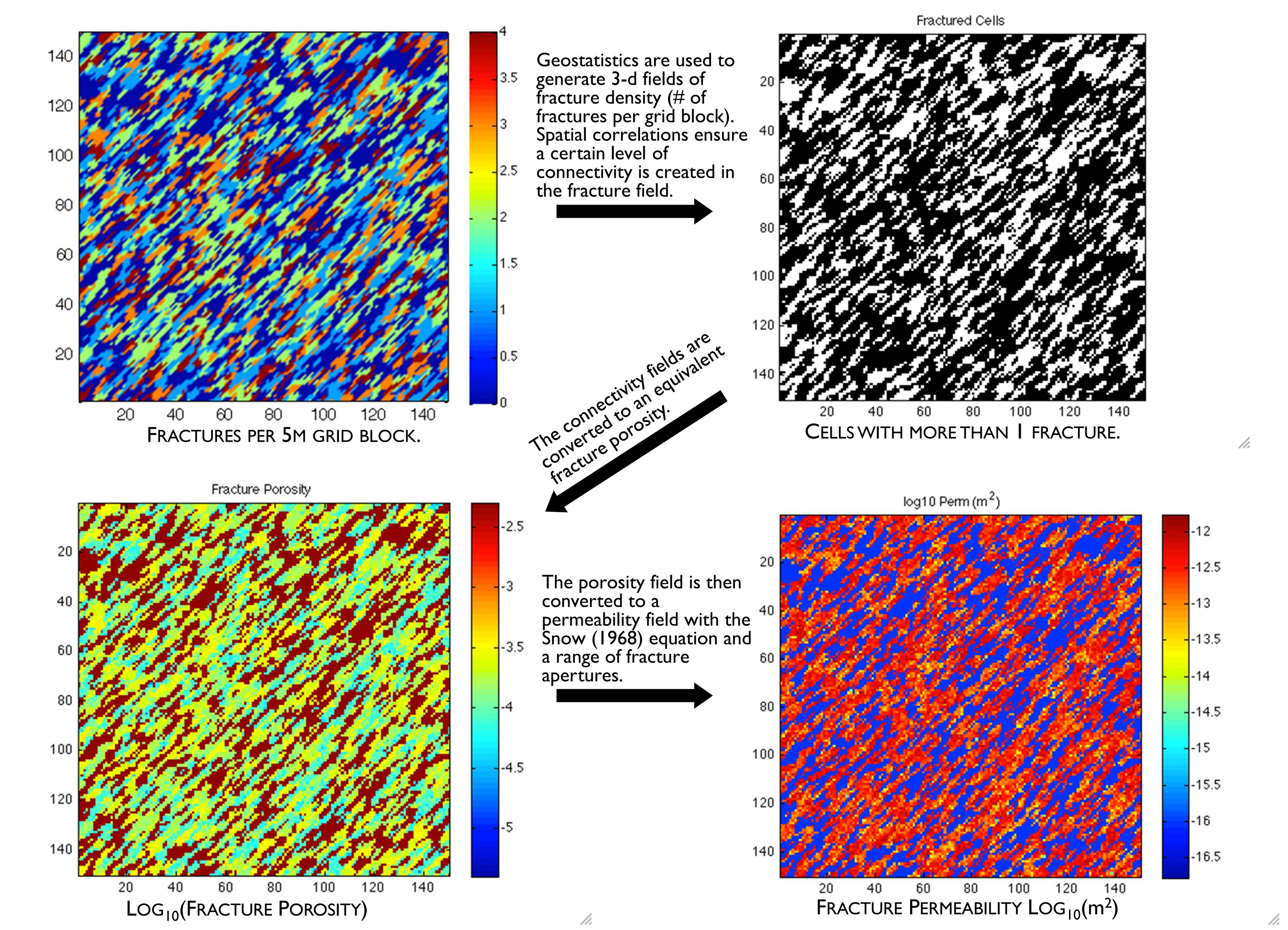


FIGURE 7 – Geostatistical approach to generating fracture permeability ensembles. The permeability fields are used as input to TOUGH2 to simulate multi-phase heat transfer across a wide range of physical and operational conditions.

5. CONNECTING TO OTHER TECHNOLOGIES AND ANALYSES

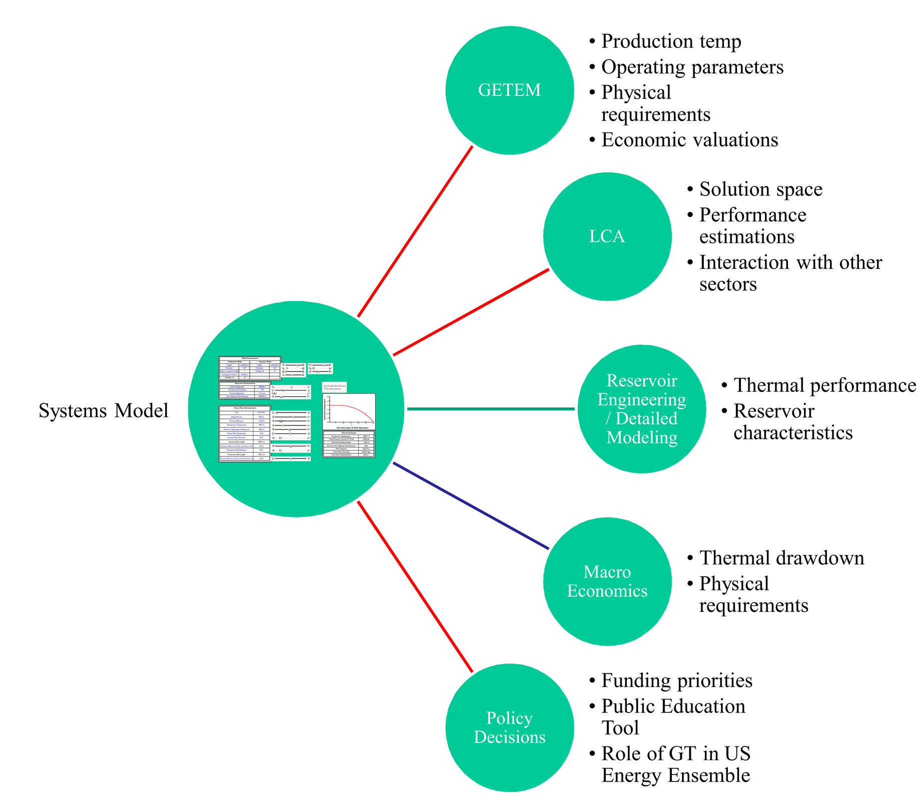


FIGURE 8 – The multi-tiered approach is designed to use, and be used by, other technologies, analyses, and simulations. The model can be used for scenario analysis, site evaluation, and risk analysis as well as for preliminary design and engineering assessment. The first beta version is scheduled to be available by the end of 2010.

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