

	Well Chara	cteristics							
Production V	Vells	Injection	Wells						
Depth	4,000.00 m	Depth	4,000.00 m	<₽		- 🗘 🛛 🗢 —		- 🖒	
Diameter	7.5"	Diameter	10.0"	$\Diamond$		· 🗘 🛛 🗘 🗇 🕞 –		- 🖒	
Ratio to Injection Wells	2	Number of	2	<-□		· 🗘 🛛 🗘 🕞 –		- 🖒	
Production Interval	675.00 m			<>──		- 🖙			
Number of	4					I			
Bess	rvoir Characte	ristics		-			Calcu	ulate Well Distance	
Reservoir Characteristics		225.00 C				r`>		et Well Distance	
Fractures per Pro		5.0			_	🖒			
Fracture Aper		0.27 mm				🖒		Keep Flow Rate Steady	
User Defined Total Mass	Flow Rate	180.00 kg/s				🖒		Keep Power Production Stea	dv
User Defined Well	Distance	3,468.75 m		— <u>ī</u> —		🖒		Keep rower rioudcuoir Stea	uy
	r Plant Charact	eristics				r>		Mass Flow Rate Given as User	Input
Size		20.0 MW			_	¢	-		
Design Peric	bd	30.0 yr				L>		Numerical Outpu	
Design Perio		30.0 yr 22.60 %				;		Production Temperature	215.49 C
-	ncy	,		-0			Tota	Production Temperature Pressure Loss per P/I Well	215.49 C 18.5 psi
Thermal Efficie Reinjection Tempe	ncy rature	22.60 %		-0			Total	Production Temperature Pressure Loss per P/I Well Thermal Drawdown Rate	215.49 C 18.5 psi 0.06 %
Thermal Efficie Reinjection Tempe Minimum Operating Ter	ncy rature nperature	22.60 % 80.0 C 190.0 C		-0			Total	Production Temperature Pressure Loss per P/I Well Thermal Drawdown Rate User Defined Well Distance	215.49 C 18.5 psi 0.06 % true
Thermal Efficie Reinjection Tempe Minimum Operating Ter Power Plant Orien	ncy rature nperature tation	22.60 % 80.0 C 190.0 C 0.50		-0	 		Total	Production Temperature Pressure Loss per P/I Well Thermal Drawdown Rate	215.49 C 18.5 psi 0.06 %
Thermal Efficie Reinjection Tempe Minimum Operating Ter	ncy rature nperature tation	22.60 % 80.0 C 190.0 C			 }	2	Total	Production Temperature I Pressure Loss per P/I Well Thermal Drawdown Rate User Defined Well Distance Well Distance	215.49 C 18.5 psi 0.06 % true 3,468.75 m
Thermal Efficie Reinjection Tempe Minimum Operating Ter Power Plant Orien	ncy rature nperature tation neter	22.60 % 80.0 C 190.0 C 0.50				2	Total Total Use The	Production Temperature IPressure Loss per P/I Well Inermal Drawdown Rate User Defined Well Distance Well Distance Total Mass Flow Rate	215.49 C 18.5 psi 0.06 % true 3,468.75 m 133.17 kg/
Thermal Efficie Reinjection Tempe Minimum Operating Ter Power Plant Orien Injection Pipe Diar	ncy rature nperature tation meter ngth	22.60% 80.0 C 190.0 C 0.50 16.0"			 ] ]	1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1	Total Total Use The	Production Temperature IPressure Loss per P/I Well Ihermal Drawdown Rate User Defined Well Distance Well Distance Total Mass Flow Rate Power Plant Output	215.49 C 18.5 psi 0.06 % true 3,468.75 m 133.17 kg/ 17.77 MW
Thermal Efficie Reinjection Tempe Minimum Operating Ter Power Plant Orien Injection Pipe Dias Injection Pipe Le	ncy rature nperature tation meter ngth and hjection Wells	22.60 % 80.0 C 190.0 C 0.50 16.0" 1,684.4 m			 }	1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1	Total Total Use The	Production Temperature IPressure Loss per P/I Well Ihermal Drawdown Rate User Defined Well Distance Well Distance Total Mass Flow Rate Power Plant Output	215.49 C 18.5 psi 0.06 % true 3,468.75 n 133.17 kg/ 17.77 MM
Thermal Efficie Reinjection Tempe Minimum Operating Ter Power Plant Orien Injection Pipe Diaa Injection Pipe Le Elevation Difference bit Plant	ncy rature nperature tation meter and Injection Wells ameter	22.60 % 80.0 C 190.0 C 0.50 16.0" 1,684.4 m 0.0 m				1) 12 12 12 12 12 12 12 12 12 12 12 12 12	Total Total Use The	Production Temperature IPressure Loss per P/I Well Ihermal Drawdown Rate User Defined Well Distance Well Distance Total Mass Flow Rate Power Plant Output	215.49 C 18.5 psi 0.06 % true 3,468.75 n 133.17 kg/ 17.77 MM

#### **Systems Engineering**

May 19, 2010

This presentation does not contain any proprietary confidential, or otherwise restricted information.

#### Thomas S. Lowry Sandia National Laboratories

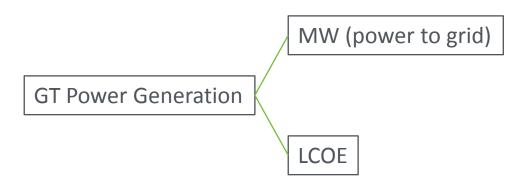
Analysis, Data System and Education

#### Overview

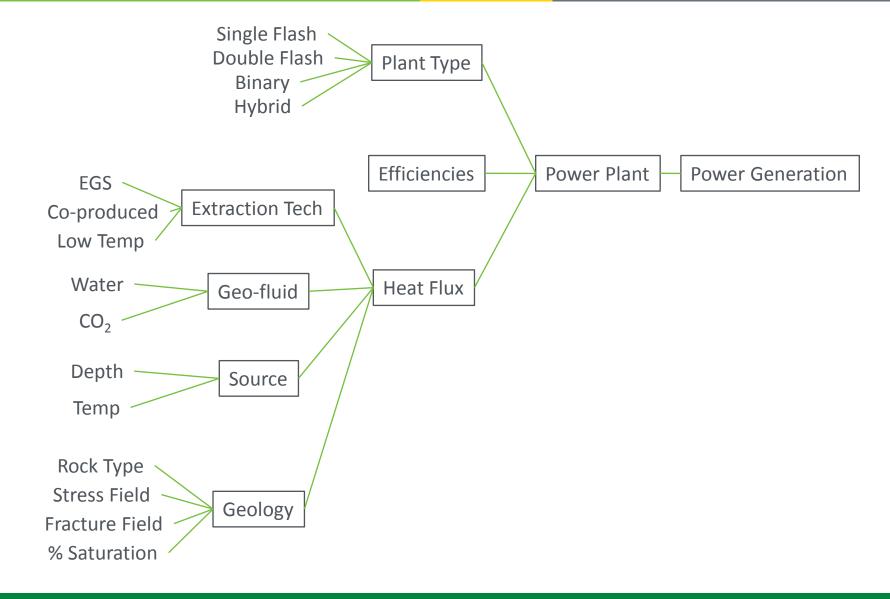
- Timeline
  - FY09 (July Sept.): Demonstration Study
  - FY10: Year 1 Implementation
- Budget
  - FY09: \$125,000, DOE Annual Operating Plan
  - FY10: \$500,000, DOE Annual Operating Plan
- GTP Barriers Addressed
  - Integration of analytical capabilities
  - Technological and institutional barriers
- Partners
  - No official co-funded partners
  - Integrating closely with INEL (GETEM) and NREL (Spatial data analysis)



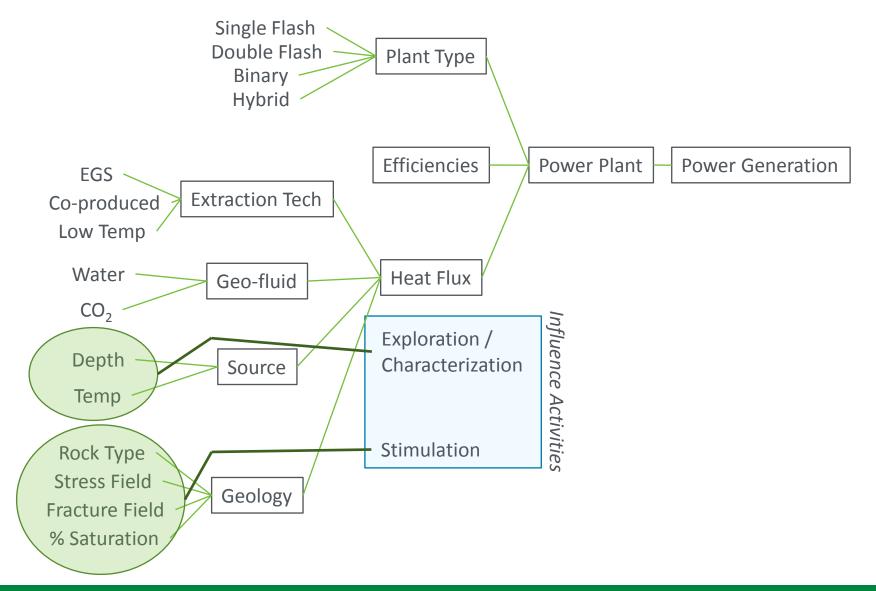
- Build off of FY09 Demonstration Project to create an interactive, physics based, systems analysis tool for geothermal energy development that will:
  - Identify 'points of attack' to maximize efforts and investment dollars
  - Identify the parameter space where geothermal energy production is physically and economically viable
  - Provide a platform for public education and interaction



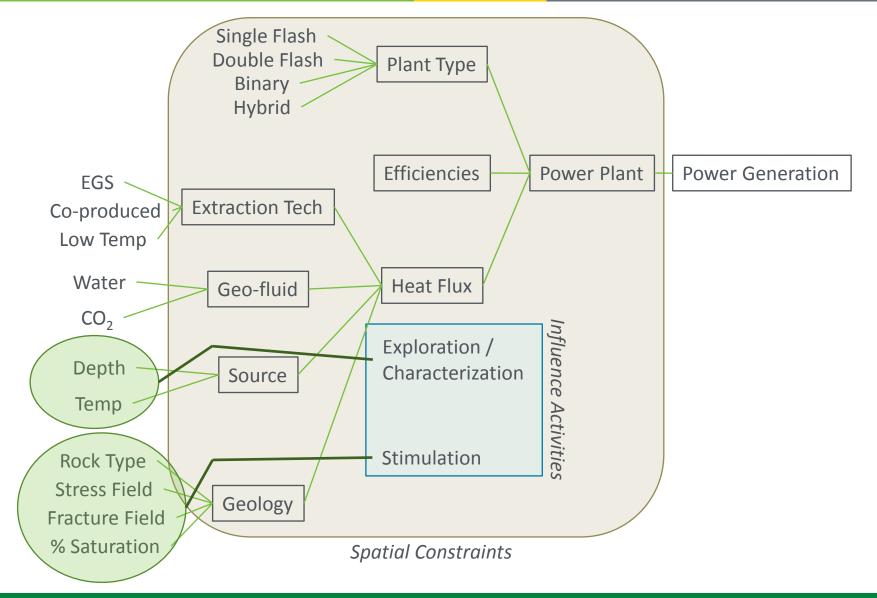




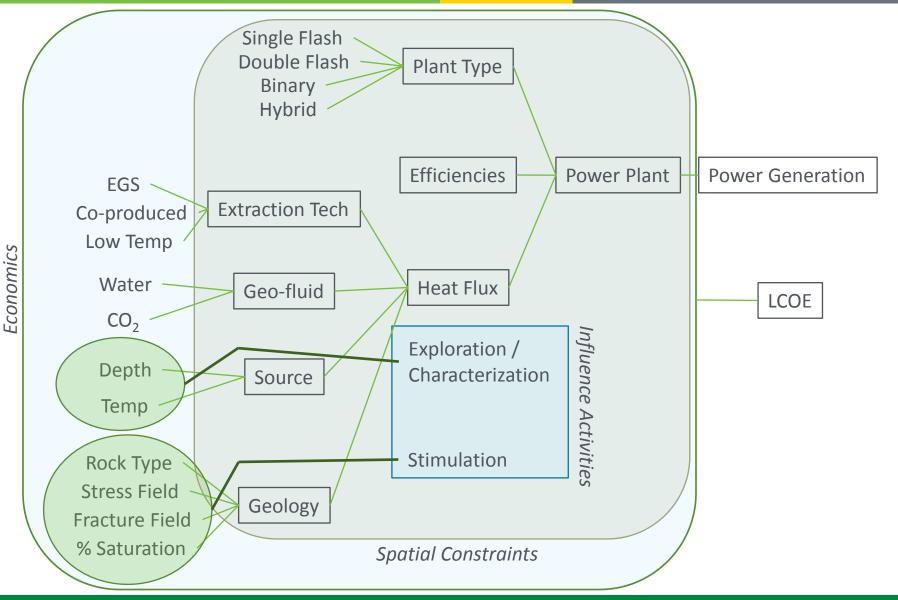






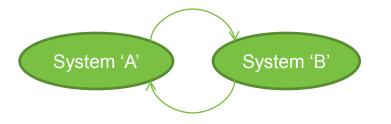






#### SYSTEM DYNAMICS APPROACH

- SD captures the temporal dynamics between connected systems and sub-systems
- Temporal dynamics capture direct influences, as well as feedbacks and delays and are defined by 'causal loops' (pde's)
- SD is easily scalable to the spatial or temporal scale of interest
- Deployable to multiple users
- GT energy production is comprised of many, integrated causal loops, across a wide range of temporal and spatial scales



Schematic of a causal loop where the state of system 'A' is dependent on the state of system 'B', which in turn is dependent on the state of system 'A'

$$\boxed{\frac{\partial A}{\partial t} = mB + n \quad \frac{\partial B}{\partial t} = pA + q}$$

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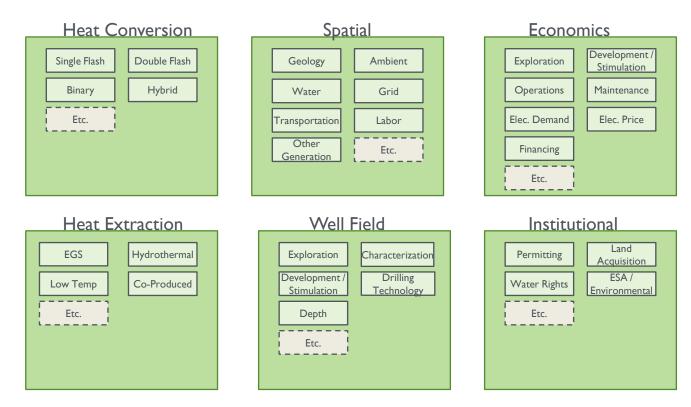
**Renewable Energy** 

Mathematically, a causal loop can be represented as a system of partial differential equations.

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- System Dynamics: Focus on feedbacks, interdependencies, and temporal dynamics
- Modular, multi-tiered approach



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### Scientific/Technical Approach



- Discrete, user-defined scenario's
- Simulate only the systems of interest Tier 2 components

<u>     Heat Conversion</u>	Spatial	Economics
Single Flash     Double Flash       Binary     Hybrid	GeologyAmbientWaterGridTransportationLaborOther GenerationEtc.	Exploration       Development / Stimulation         Operations       Maintenance         Elec. Demand       Elec. Price         Financing       Etc.
Heat Extraction EGS Hydrothermal Low Temp Co-Produced	Exploration       Characterization         Development / Stimulation       Drilling Technology         Depth       Etc.	Institutional         Permitting       Land Acquisition         Water Rights       ESA / Environmental         Etc.       J

#### Scientific/Technical Approach



- Each system is composed of multiple Tier's
- Successive Tier's represent increases in resolution

Heat Conversion	Spatial	Economics
Single Flash       Double Flash         Binary       Hybrid         Etc.       Image: State of the stat	GeologyAmbientWaterGridTransportationLaborOther GenerationEtc.	Exploration       Development / Stimulation         Operations       Maintenance         Elec. Demand       Elec. Price         Financing       Etc.
EGS       Hydrothermal         Low Temp       Co-Produced         Etc.       Huddress	Bit Design       Casing Tech.         Isolation       Steering         Logging / Imaging       Etc.	Institutional          Permitting       Land         Vater Rights       ESA /         Etc.       Etc.

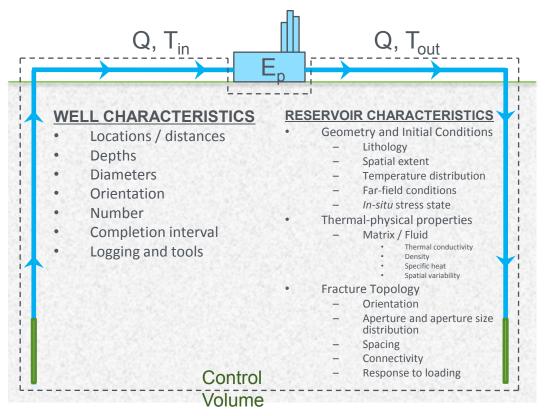
### Scientific/Technical Approach



- Discrete, user-defined scenario's
- Simulate only the systems of interest

Binary Plant	Spatial	Economics
Preheater Evaporator Turbine Condenser	Geology Ambient Water Grid	ExplorationDevelopment / StimulationOperationsMaintenance
Cooling Etc.	Transportation   Labor     Other   Etc.     Generation   Image: State	Elec. Demand Elec. Price
Heat Extraction	Well Field	Institutional
EGS Hydrothermal Low Temp Co-Produced	Exploration       Characterization         Development / Stimulation       Drilling Technology         Depth       Etc.	Permitting Land Acquisition Water Rights ESA / Environmental





#### CURRENT FUNCTIONALITY

- EGS
- Simulates everything but the power plant
- Scenario Definition
  - Power plant size and efficiency
  - Resource depth and temperature
  - Plant effluent temperature
  - Number of injectors
  - Ratio of producers to injectors
  - Pipe and borehole diameters
  - Borehole pumping
  - Time span
- Model Outputs
  - Thermal drawdown
  - Reservoir lifespan
  - Pressure distribution throughout the system
  - Energy production

Production Temperature

- Carslaw and Jaeger<sup>1</sup>
- Gringarten et al.<sup>2</sup>
- Pressure is set to keep GF liquid w/in EGS and wells (no flash)
- Snow<sup>3</sup> estimate for permeability of reservoir
- Head loss in pipes and wells based on Darcy-Weisbach Eqn. using the Jains<sup>4</sup> approximation for *f*

- Outputs
  - Static
    - Thermal
       drawdown rate
  - Temporal
    - Production temperature
    - Pressure
    - Plant efficiency
    - Power production

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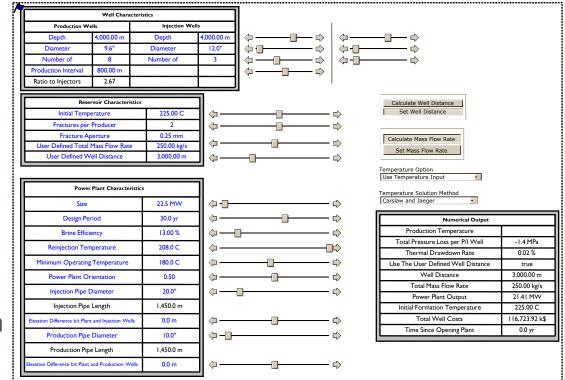
<sup>1.</sup> Carslaw & Jaeger, 1959, Conduction of Heat in Solids

<sup>2.</sup> Gringarten, A.C., P.A. Witherspoon, Y. Ohnishi, 1975, Theory of Heat Extraction from Fractured Hot Dry Rock, J. Geophys. Res., 80(8)

<sup>3.</sup> Snow, D.T., 1968, Rock fracture spacings, openings, and porosities, J. Soil Mech. Found. Div., Proc. Amer. Soc. Civil Engrs., 94, pp. 73-91

<sup>4.</sup> Jain, A.K., 1976, Accurate explicit equation for friction factor. J. Hyd. Div., 102(HY5), pp. 674-77

- User Interface
  - Problem Definition
  - Solution Method
    - Gringarten
    - C & J
  - Options to Calculate
    - Well Distance
    - Reservoir Size
    - Mass Flow Rate
    - Power Generation
  - Simulation Type
    - Deterministic
    - Stochastic



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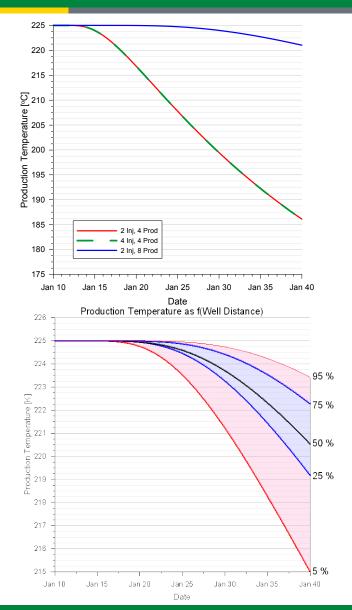
**ENERGY** 

Energy Efficiency &

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- Producer to Injector Analysis P/I Diameter [in] Scenario P/I Number 2/4 8.5 / 12.0 1 4/4 8.5/8.5 2 3 8/2 6.0 / 12.0 P/I Depth [m] 4000 Production Interval [m] 800 Initial Temp [°C] 225 # of Fractures 4 Aperture [mm] 0.27 Mass Flow Rate [kg/s] 250 Well Distance [m] 3000 Plant Size [MW] 20 **Plant Efficiency** 13% I/O Pipe Diam [in] 10/20
- Stochastic / Uncertainty
  - Scenario 3 Inputs
  - Well distance input as a normally distributed, stochastic variable,  $\mu$  = 3000 m,  $\sigma$  = 300



### **Project Management/Coordination**

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- Schedule
  - Schedule is behind for FY10 due to funding delays (Money received in March, 2010)
  - Currently ~10% complete
- Application of Resources
  - Sandia Earth Systems Department: Project management, systems modeling and integration
  - Sandia Geothermal Department: Reservoir modeling, industry connections, project oversight
- Project Integration
  - Leverage detailed modeling efforts at Sandia
  - Leverage and link to INEL and the GETEM model, LBNL exploration activities, NREL spatial analysis, and ANL life-cycle analysis
- Coordination with Industry
  - Expert solicitation
  - Systems recommendations

#### **Future Directions**

- FY10
  - Create 'beta' version of the current model and distribute to DOE GTP for comment (May-June)
  - Meet with other labs who are working on specific component level tasks to identify linkages and points of connection (May-Sept.) – One key linkage is with INEL and GETEM
  - Meet with industry experts to gather feedback on which components to include and in what priority they need to be developed (May-Sept.)
  - Develop Tier 2 functionality of the Power Plant module (August)
  - Add higher fidelity reservoir dynamics for heat extraction (August)
  - Begin work on the spatial (geology only), and economic modules (June)
  - Create new beta version (Sept.)
- FY11
  - Continue work on each of the modules, utilizing industry input and DOE feedback to prioritize the development process (Ongoing)
  - Complete the Tier 2 modules for Heat Conversion, Heat Extraction, Well Field, and Economics modules (June, 2011)
  - Finalize the GUI to control the Tier 2 functionality (August, 2011)
  - Begin work on the balance of the spatial module and the institutional module (Sept. 2011)
  - Create a Tier 2 distributable model for public consumption (Sept, 2011)
- FY12 and beyond
  - Add Tier 3 and higher functionality as appropriate (Ongoing)
  - Maintain distribution version (Ongoing)
  - Perform analyses and simulations as requested (Ongoing)

#### Mandatory Summary Slide



- Create an interactive, physics based, systems analysis tool for geothermal energy development
- Provide a tool that will:
  - Identify 'points of attack' to maximize efforts and investment
  - Identify the parameter space where geothermal energy production is physically and economically viable
  - Provide a platform for public education and interaction
- Using a System Dynamics approach, the tool will focus on the temporal dynamics between the many systems and subsystems
- Implemented using a multi-Tiered modular approach that will simulate varying levels of resolution and detail depending on the relative impact of each system
- Still in the initial phases of development with a beta-version of a simplified EGS system to be available in June, 2010