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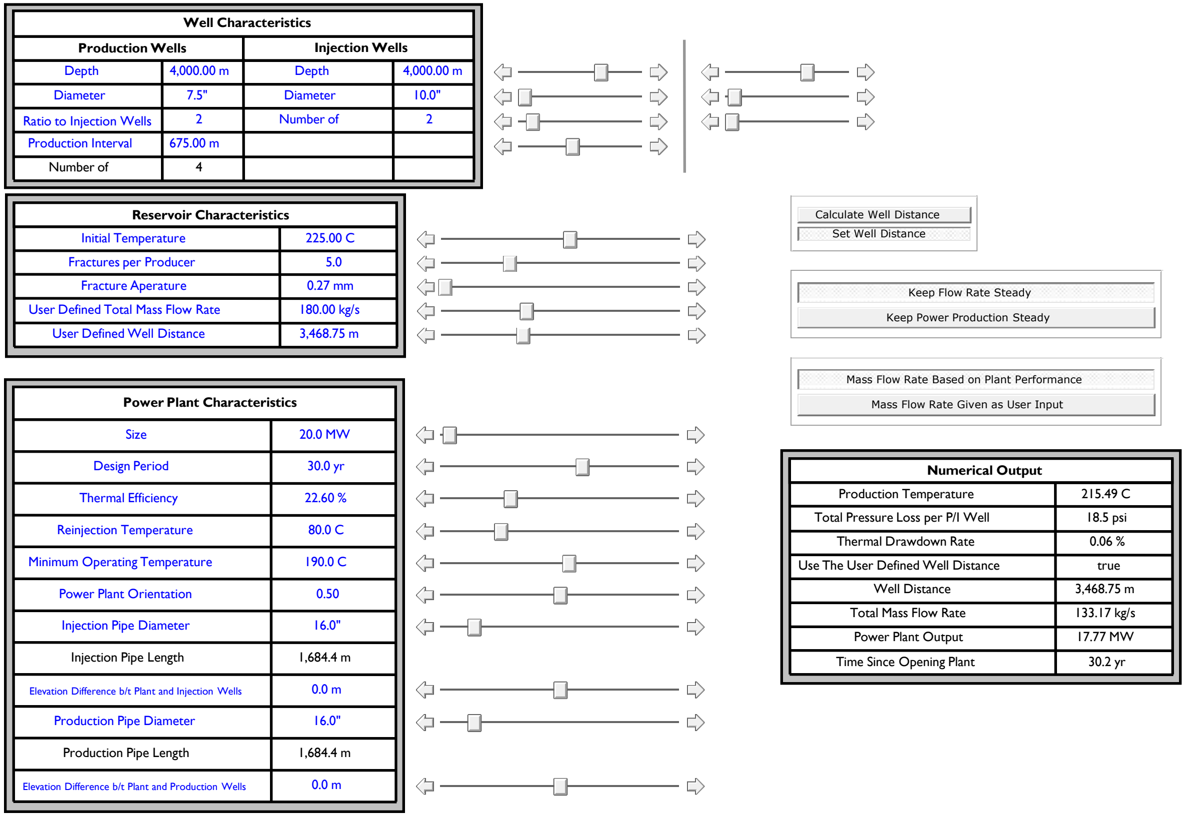

Systems Engineering

May 19, 2010

Thomas S. Lowry

Sandia National Laboratories

Analysis, Data System and Education

Overview

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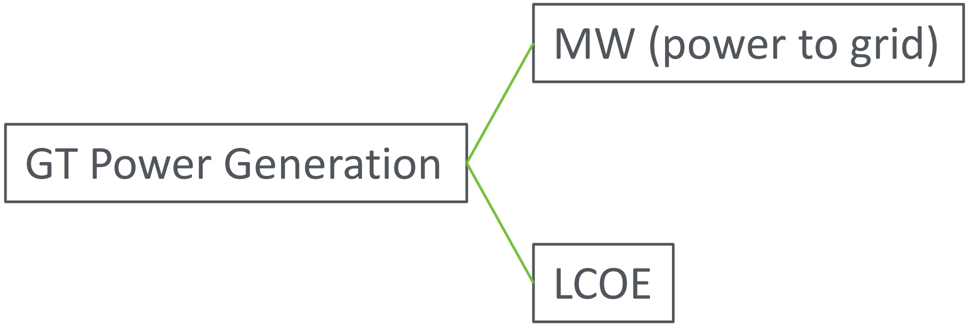
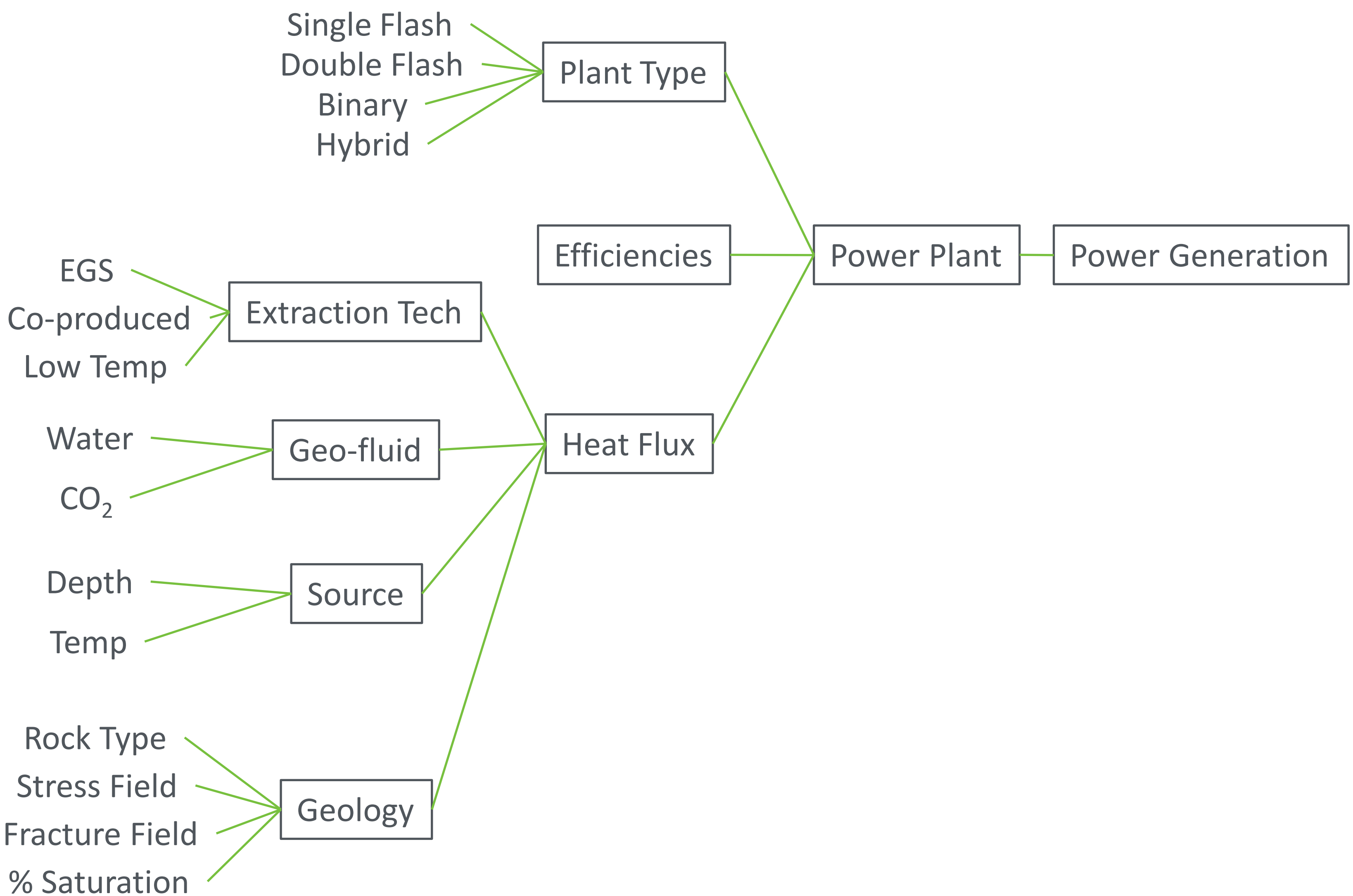
- Timeline
  - FY09 (July – Sept.): Demonstration Study
  - FY10: Year 1 Implementation
- Budget
  - FY09: $125,000, DOE Annual Operating Plan
  - FY10: $500,000, DOE Annual Operating Plan
- GTP Barriers Addressed
  - Integration of analytical capabilities
  - Technological and institutional barriers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

Relevance/Impact of Research

- 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



Relevance/Impact of Research



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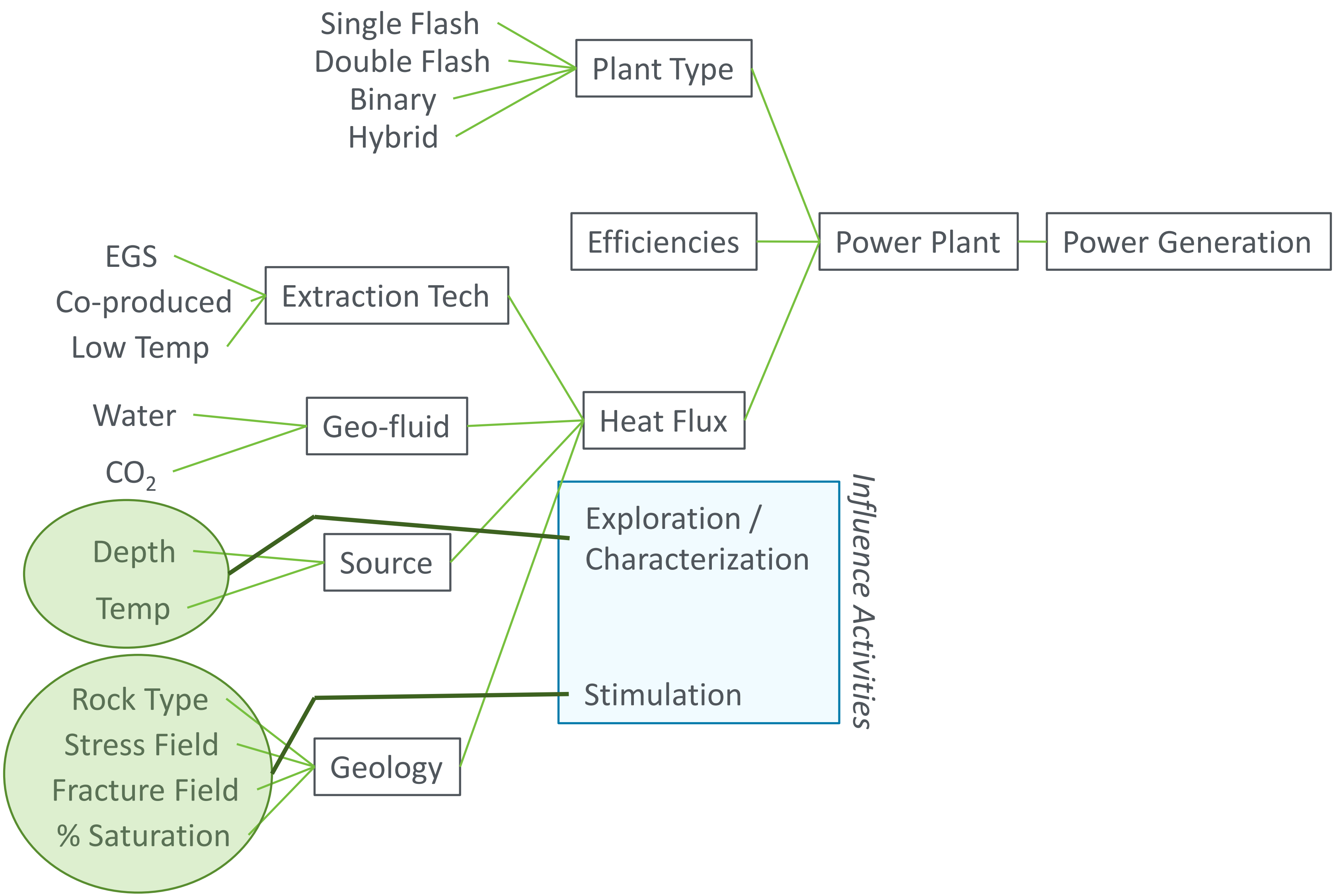

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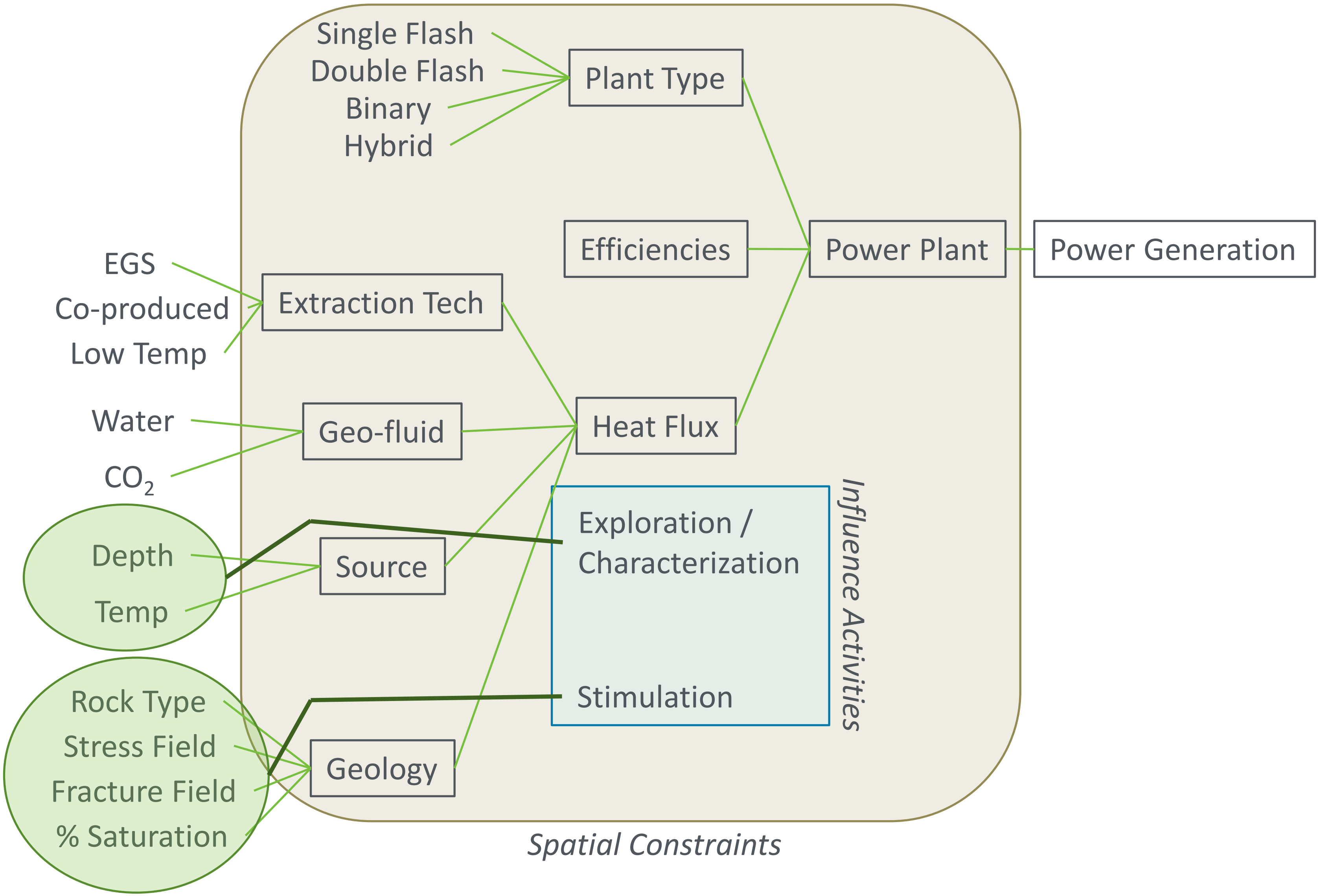

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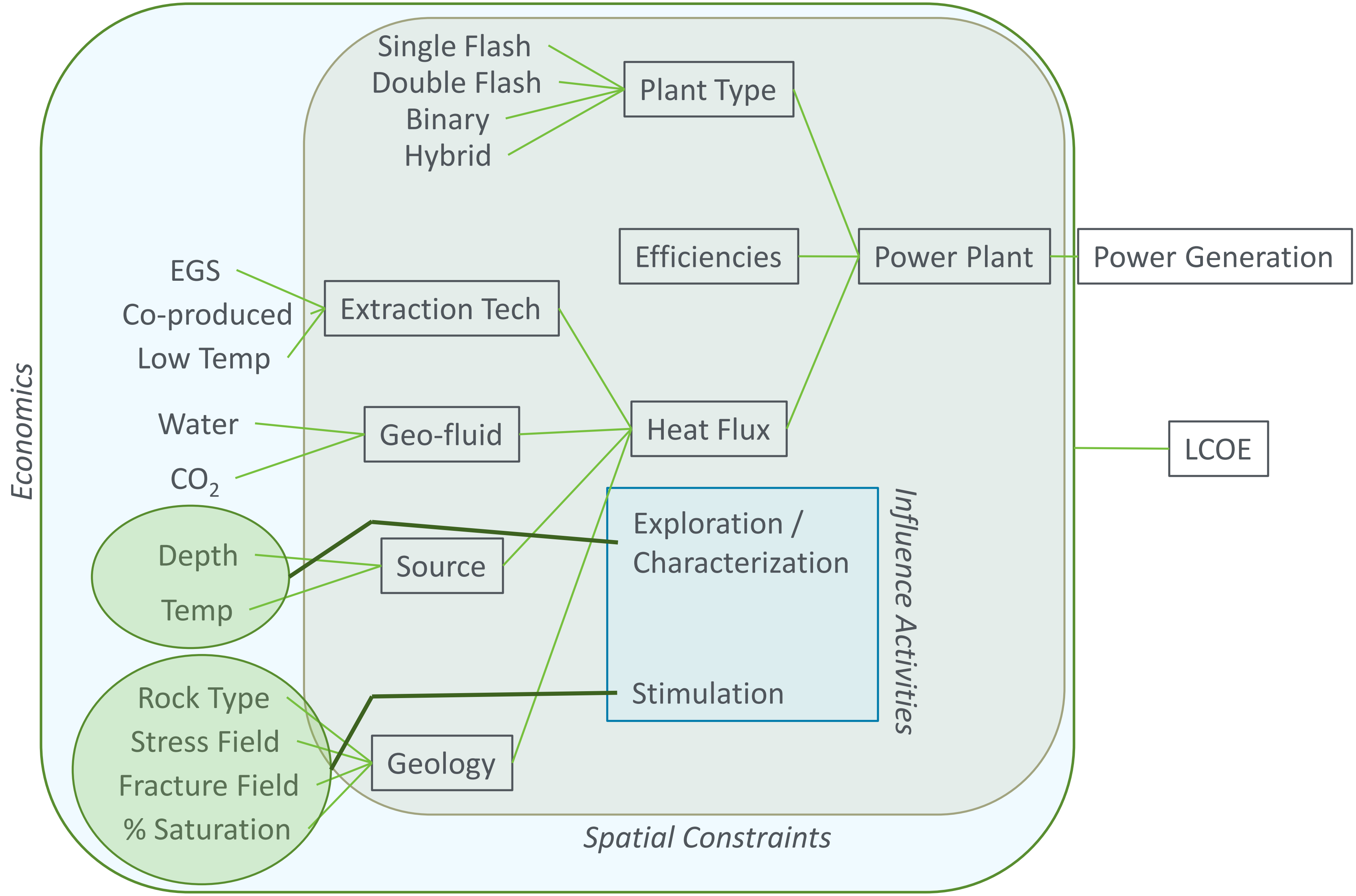
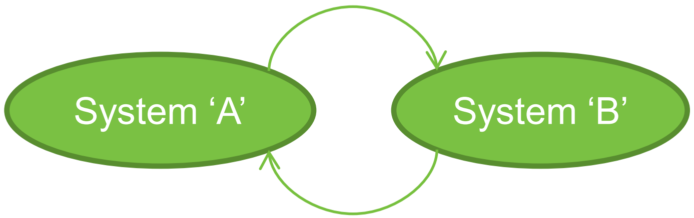


SYSTEM DYNAMICS APPROACH

- 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



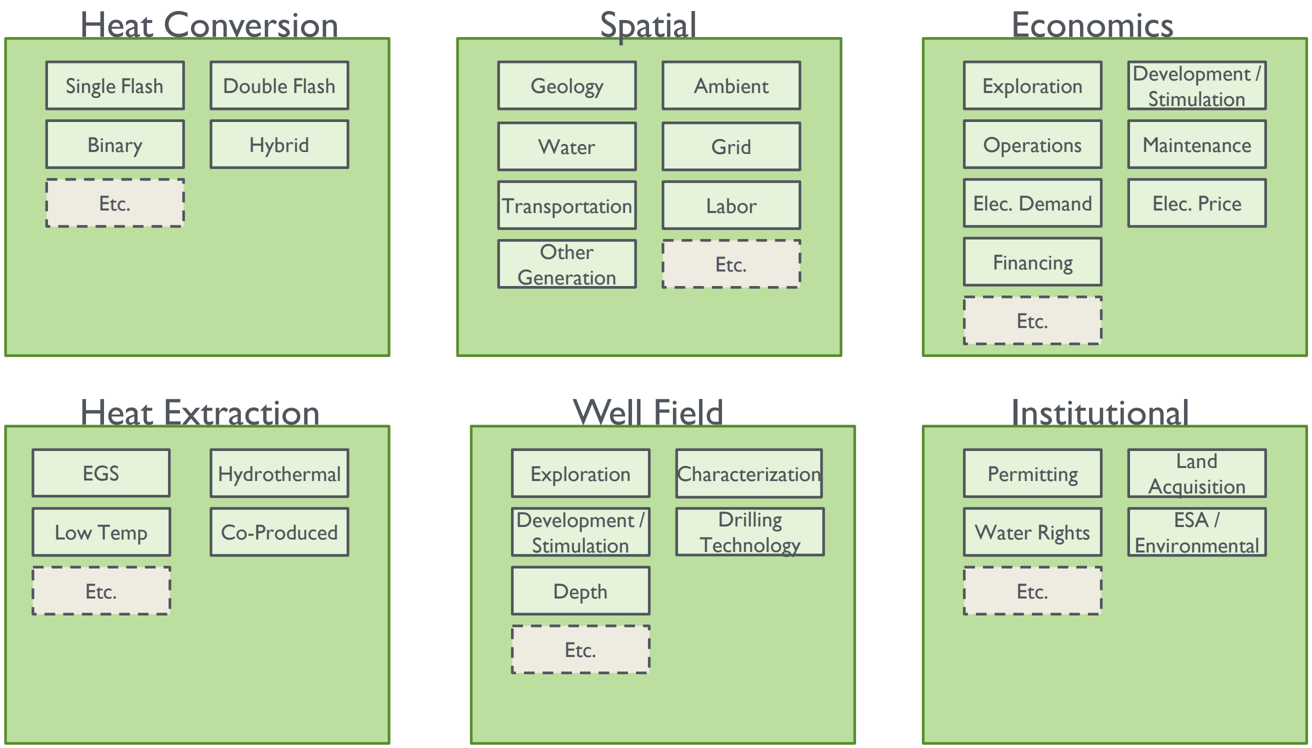
Schematic of a causal loop where the state of system 'A' is dependent on the state of system 'B', which in turn is dependent on the state of system 'A'

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

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

Scientific/Technical Approach

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



Scientific/Technical Approach

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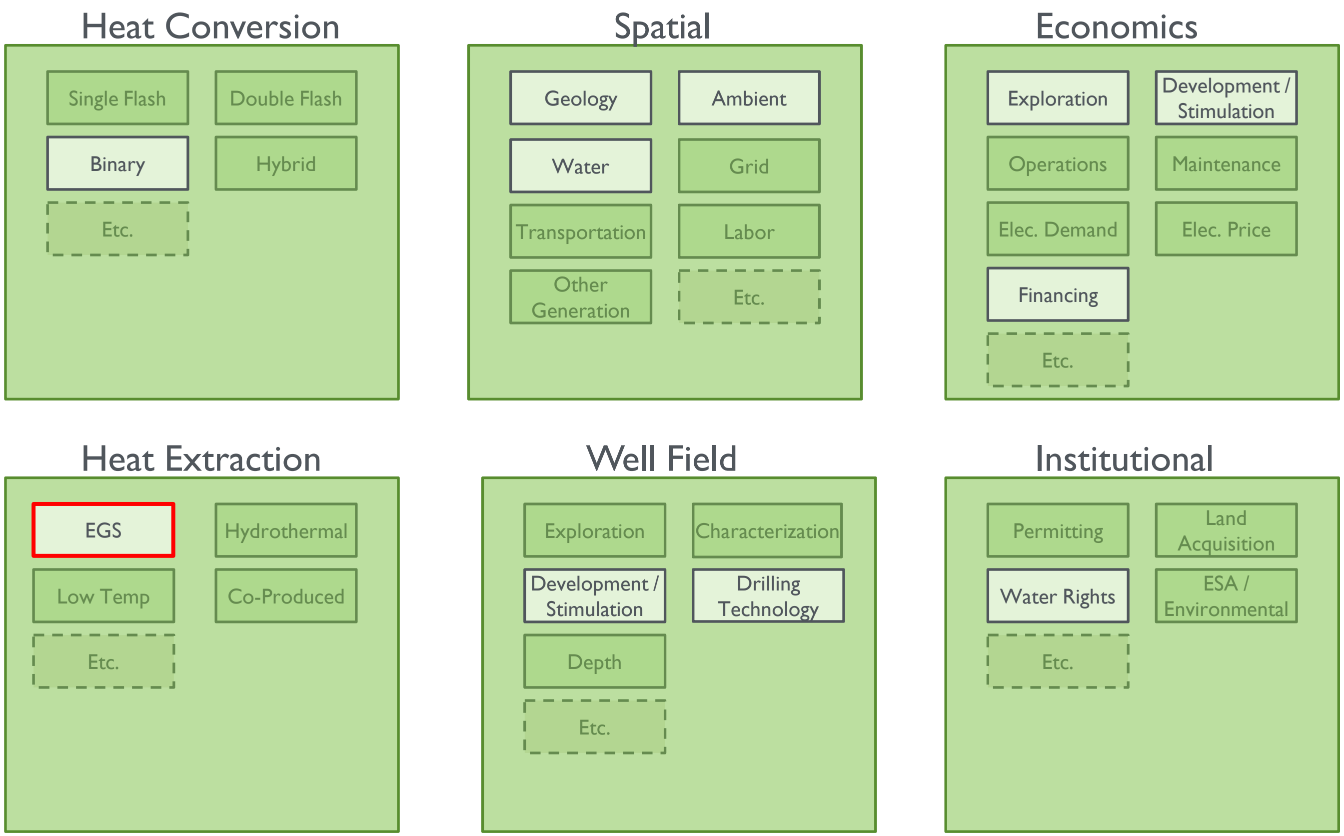
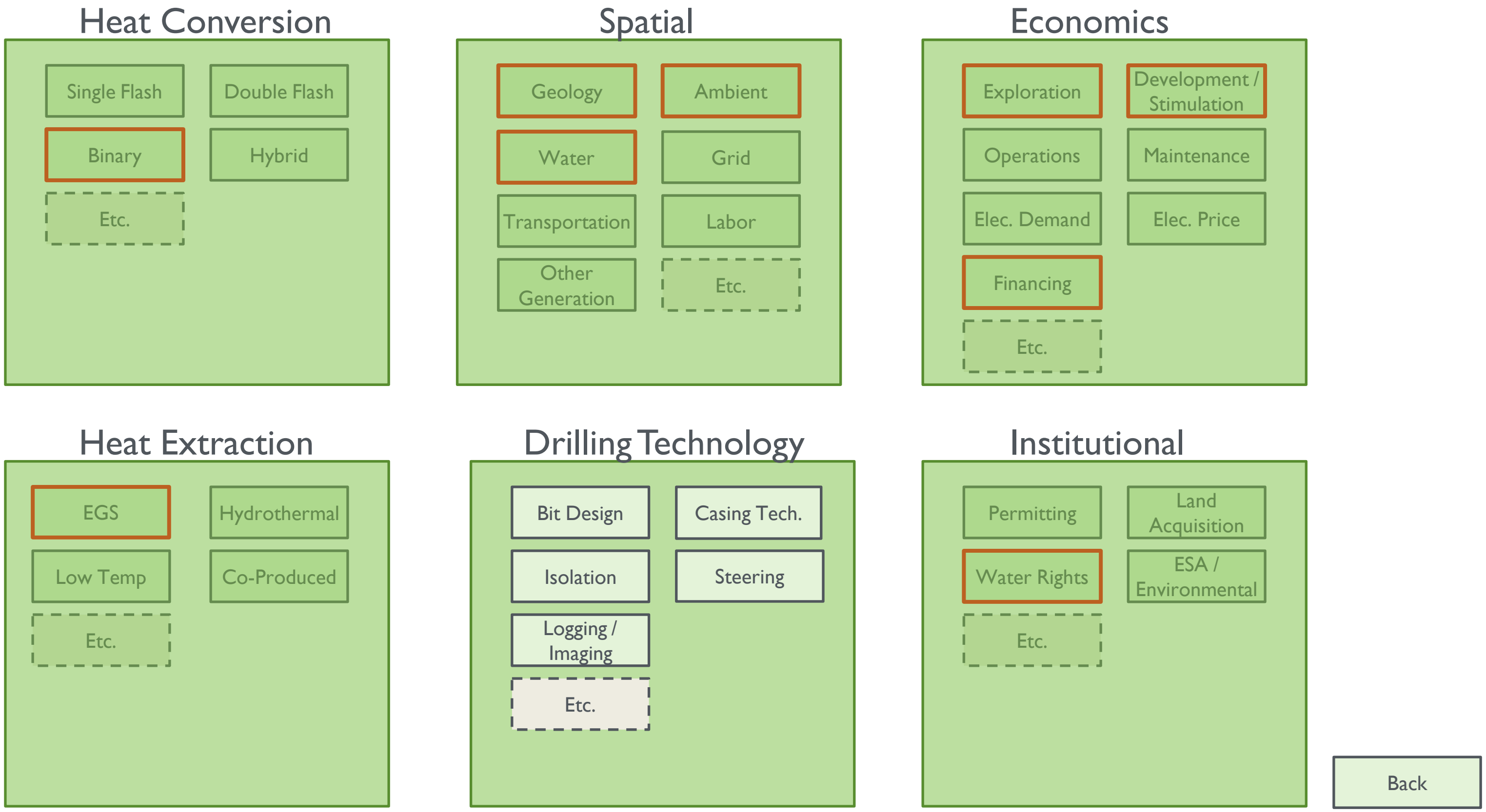
- Discrete, user-defined scenario's
- Simulate only the systems of interest – Tier 2 components



Scientific/Technical Approach

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



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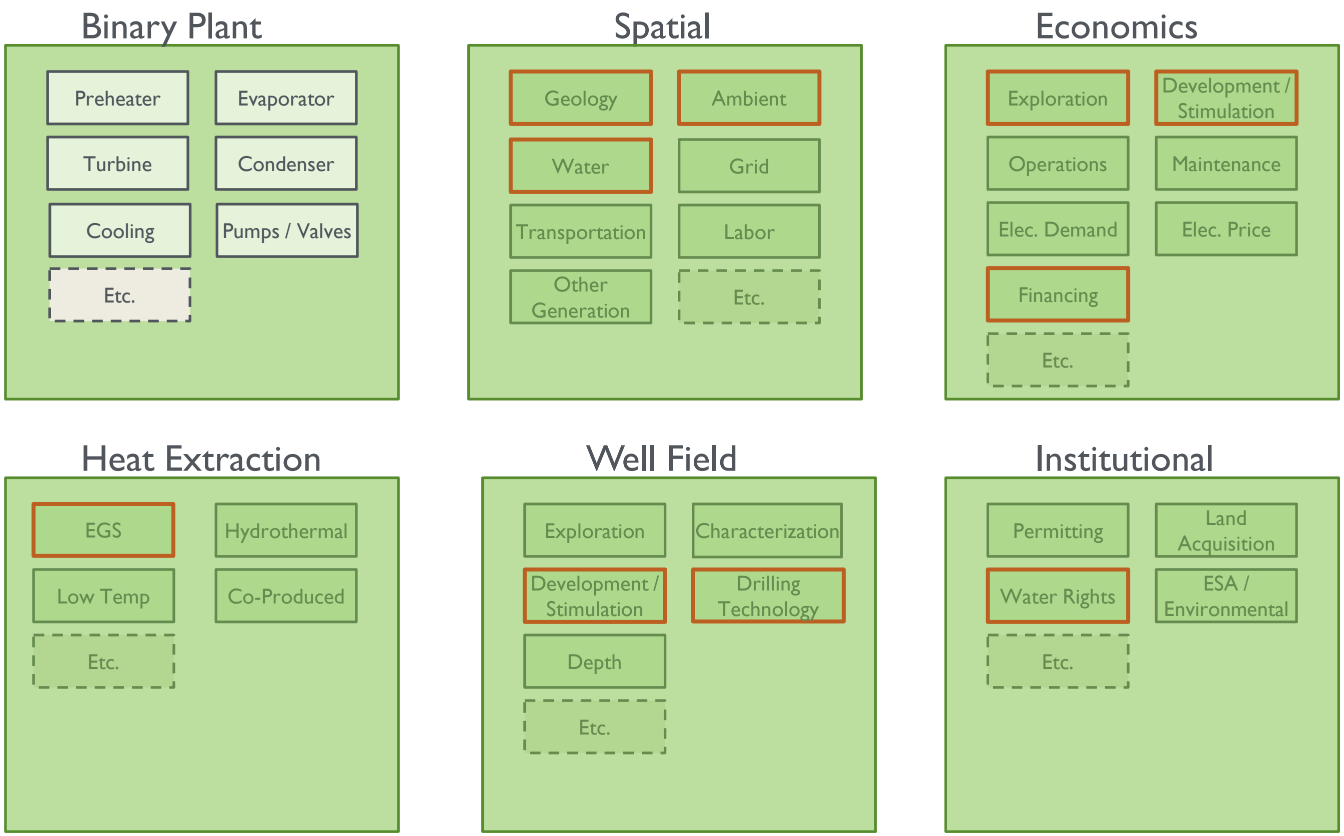

Accomplishments, Expected Outcomes and Progress

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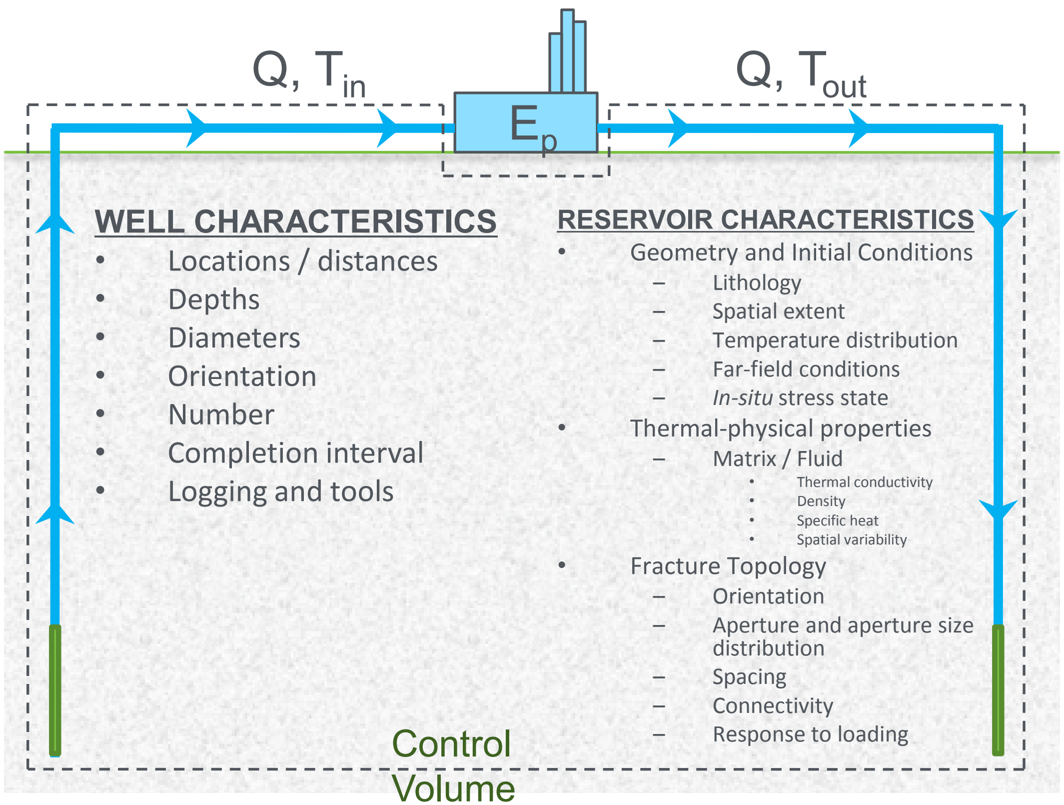


CURRENT FUNCTIONALITY

- 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

Accomplishments, Expected Outcomes and Progress

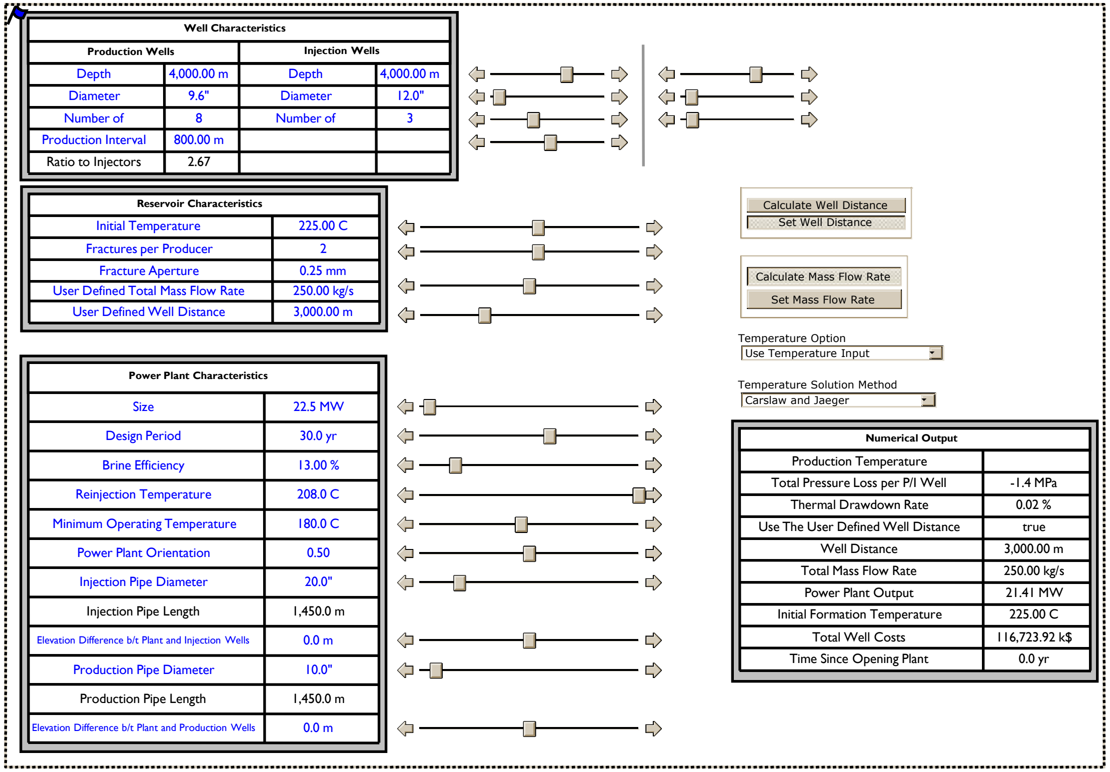
- Production Temperature
  - Carslaw and Jaeger[1]
  - Gringarten et al.[2]
- Pressure is set to keep GF liquid w/in EGS and wells (no flash)
- Snow[3] estimate for permeability of reservoir
- Head loss in pipes and wells based on Darcy-Weisbach Eqn. using the Jains[4] approximation for *f*

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

1. Carslaw & Jaeger, 1959, Conduction of Heat in Solids
2. Gringarten, A.C., P.A. Witherspoon, Y. Ohnishi, 1975, Theory of Heat Extraction from Fractured Hot Dry Rock, *J. Geophys. Res.*, 80(8)
3. Snow, D.T., 1968, Rock fracture spacings, openings, and porosities, *J. Soil Mech. Found. Div., Proc. Amer. Soc. Civil Engrs.*, 94, pp. 73-91
4. Jain, A.K., 1976, Accurate explicit equation for friction factor. *J. Hyd. Div.*, 102(HY5), pp. 674-77

Accomplishments, Expected Outcomes and Progress

- 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



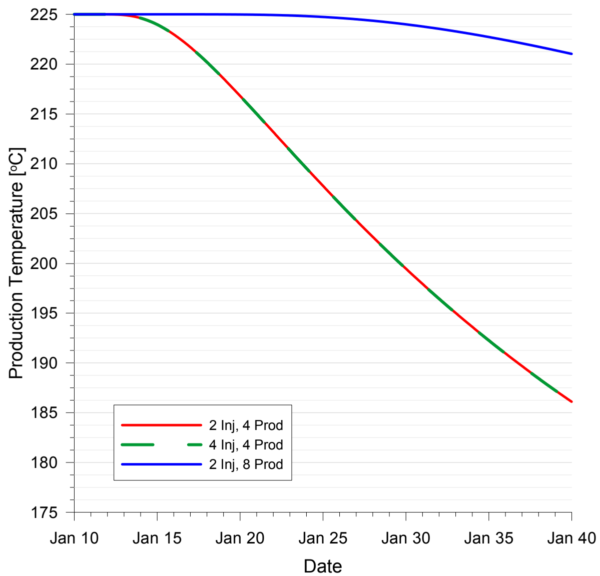
Accomplishments, Expected Outcomes and Progress

- Producer to Injector Analysis

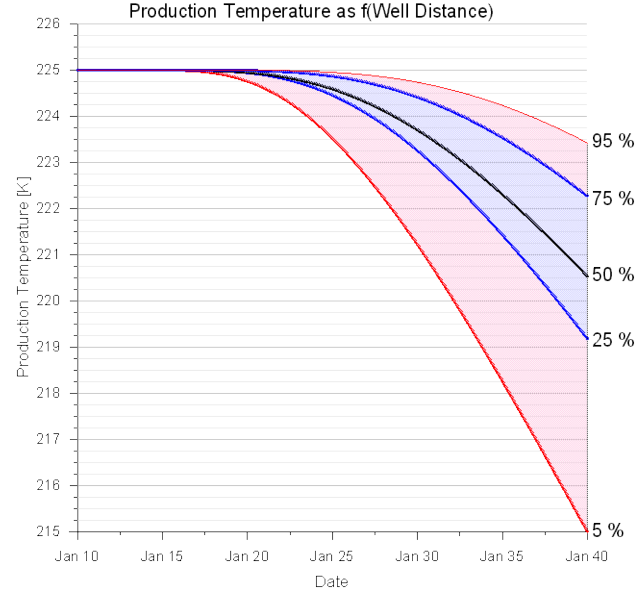
Scenario	P/I Number	P/I Diameter [in]
1	2 / 4	8.5 / 12.0
2	4 / 4	8.5 / 8.5
3	8 / 2	6.0 / 12.0

P/I Depth [m]	4000
Production Interval [m]	800
Initial Temp [^oC]	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, μ = 3000 m, σ = 300



Production Temperature as f(Well Distance)



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

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- 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 sub-systems
- 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