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Further Developments on the Geothermal System Scoping Model

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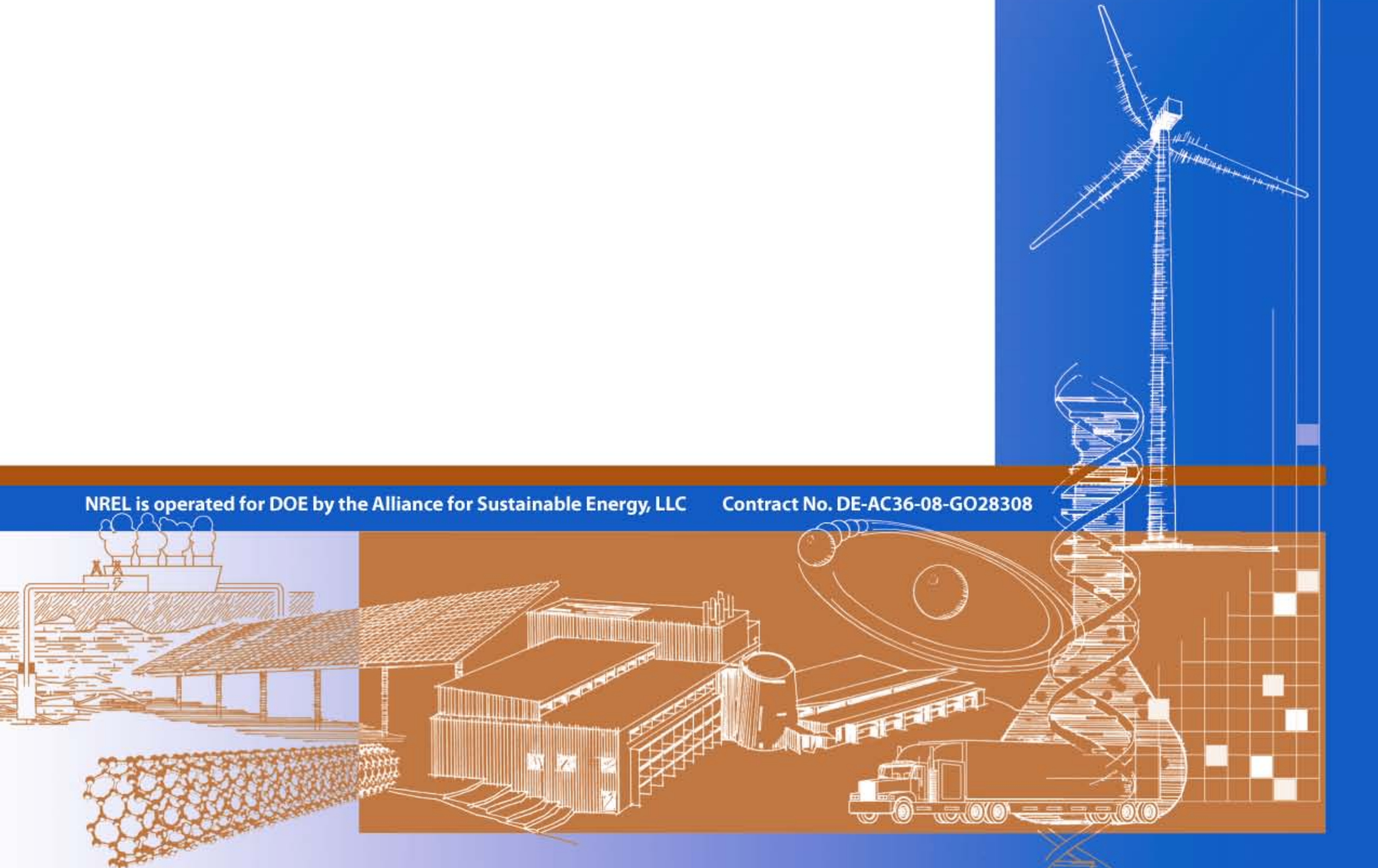

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Further Developments on the Geothermal System Scoping Model

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ABSTRACT

The fields of well construction and engineering, power plant construction and engineering, and reservoir engineering often proceed independently of one another. Yet the subsystems of a geothermal plant with which each of these fields is concerned need to be integrated in order to create a viable geothermal power system and make enhanced (or engineered) geothermal systems (EGS) a technical and an economic reality. Furthermore, each of these subsystems need to be examined in the context of the overall power system to aid with plant construction, and–more salient to the U.S. Department of Energy–to help determine best investment of research dollars.

In further development of a high-level model begun in collaboration between the National Renewable Energy Laboratory (NREL) and Sandia National Laboratories (SNL), refinements of the Geothermal System Scoping Model (GSSM) are presented. GSSM uses a lumped-parameter approach to examine the interactions among the several subsystems of a putative EGS. This effort will provide a means for performing a variety of trade-off analyses of surface and subsurface parameters, sensitivity analyses, and other systems engineering studies in order to better inform R&D direction and investment for the development of geothermal power into a major contributor to the U.S. energy supply.

GSSM is not a design tool, but rather is intended to search over broad parameter spaces to determine the technical, and to a more limited extent, economic feasibility of a wide range of geothermal power configurations. The model does not make any assumptions as to the type of geothermal power being used. Thus, whether the system considered is hydrothermal, EGS, or co-produced fluids is not explicitly considered, although the inputs to the model should be aligned with known characteristics of the type(s) of plant under consideration. This allows GSSM to be more broadly applied. The model is complementary to ongoing work at SNL, which is more strongly focused on EGS.

Early results of the application of GSSM to the Geothermal Technologies Program's technical baseline are also presented.

INTRODUCTION

There has been an increased interest and investment in geothermal power in recent years. In some cases this increase has been dramatic. For example, the U.S. Department of Energy's (DOE) Geothermal Technologies Program (GTP) has seen a striking increase in its omnibus funding from near zero in 2007 to some $50 million in fiscal year (FY) 2010. In addition, the American Re-investment and Recovery Act (ARRA) allotted $400 million to GTP in FY 2009, over and above its omnibus funding. This interest has in part been sparked by the publication of the seminal Massachusetts Institute of Technology (MIT) study sponsored by DOE, *The Future of Geothermal Energy*, which describes enhanced, or engineered, geothermal systems (EGS)[1].

The purpose of this work is to develop a simple, flexible, high-level geothermal systems model to enable the performance of trade studies and sensitivity analyses among the various components and parameters of a geothermal power station. For example, questions such as "How does the efficiency of the power plant affect the total number of wells that need to be drilled in order to build a profitable plant from a given reservoir, and what is the optimal ratio of producers to injectors?" or "How does the shape of a reservoir affect the power it can deliver?" The Geothermal Systems Scoping Model (GSSM), still under development, can help answer questions such as these, and can inform decision-making in order to achieve GTP programmatic and national goals. Portions of this work have already been incorporated into a more sophisticated systems dynamics-based model being developed by Sandia National Laboratories (SNL).[2] This paper is a follow-up to work presented previously.[3]

DEFINITIONS AND ASSUMPTIONS

In order to construct the GSSM, a geothermal power plant design is divided into four basic design blocs based on the major subsystems of a geothermal power plant – the reservoir, the wells, which are further divided into producers and injectors, and the surface facility. The producing wells are treated separately from the injectors. The model uses a readily accessible spreadsheet program (MS Excel) and makes extensive use of lumped parameters. Thus the individual blocs are interconnected but many engineering details of each are left unspecified; the interactions among them are what are important. This is not to say that the model does not include considerable detail, but rather that the model lumps parameters together in such a way as to maximize flexibility when trying different scenarios. In this sense, GSSM is more concerned with interface engineering among the various subsystems. The idea is not to develop a complete geothermal power plant specification, but rather to study the effects of varying parameters of one part of a geothermal plant on the other parts. This enables a high-level plant description that can serve as a starting point for plant design and as a benchmark for the determination of best investment of RD&D dollars. In fact, the development of various scenarios for the latter is one of the prime motivators for this work.

The blocs indicated previously are briefly described below. This is followed by a discussion of the various simplifying assumptions for GSSM and a work-up of a 20 MWe EGS power plant scenario.

Power Plant

For the purposes of GSSM, this is defined as all heat exchangers, flash vessels, condensers, turbines and generators, plus all pumps required to move fluid internally among these components. It can be thought of as that portion of the geothermal plant between the vaporizer inlet and the condenser outlet when following the circuit of the geothermal fluid. This specifically excludes pumping requirements from the well systems (see below). The power plant efficiencies used in GSSM calculations factor in all losses between these points, including frictional and form losses, turbine efficiencies, heat loss through component exposure to atmosphere, etc.

The power plant is assumed to be located at a point very near the center of the footprint of the reservoir projected to the surface.

Injector Wells

This is the simpler set of wells for modeling purposes. The design of the well(s) is a simplified version of a well design given in a report from SNL.[4] Each is broken into three sections for the purposes of hydraulic calculations – production liners 1, 2 and 3, with a standard diameter for each section. Liner 1 is assumed to be 13 5/8 inches, or 0.346075 m, in diameter. Production liners 2 and 3 are 0.244475 and 0.1778 m, respectively. The top portion of the well is liner 1, the bottom is liner 3. Pumping requirements are calculated for the injector wells separately from the producers, but no assumption is made as to the actual location of these well pumps (well head at the injectors, downhole in the producer, etc.) It is only necessary to calculate the pumping needed.

The heads of the injector wells are assumed to be co-located with the power plant for calculation purposes.

Reservoir

This is the rock mass from which heat is drawn as well as the pore and fracture system within this mass through which the water actually passes. In terms of the system circuit, it is that portion of the system between the bottom(s) of the injector well(s) and the bottom(s) of the producer(s). For the sake of simplicity, the water is assumed to pass through the entire volume of the reservoir, and heat is also assumed to be withdrawn uniformly from the entire volume. There is no assumption as to the form of the flow circuits through the reservoir, but rather these are characterized with a bulk hydraulic conductivity, and the model for the reservoir is similar to that of a confined aquifer. Pumping requirements are calculated based on a standard formulation of bulk flow through a confined aquifer, with the density based on the average (midpoint) temperature of the fluid in the reservoir.

Producer Wells

This includes both producer wells and the overland travelers that ultimately connect the producers to the power plant. Pumping requirements for both the producer wells and the travelers are calculated in this bloc. As in the case of the injectors, no assumption is made as to the specific location(s) of the pump(s).

These blocs are conceptually arranged as shown in Figure 1. In earlier versions of GSSM, either the power plant could be selected to impose requirements on the reservoir, or the reservoir could be selected to impose constraints on the power plant, with the requirements and the constraints being mediated by the wells. This version streamlines the input while allowing both the power plant and the reservoir to be manipulated separately.

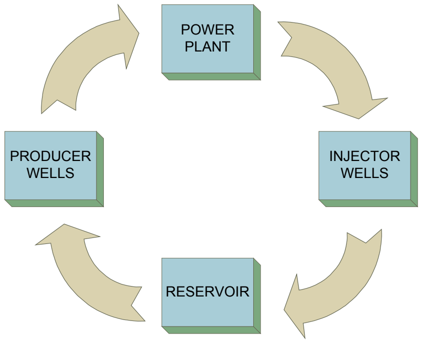


Figure 1: Conceptual layout of a geothermal power system

Thus, GSSM can be used to determine the general requirements that a potential reservoir formation must meet. However, since the actual reservoir created imposes constraints on the power plant that can be built, the reservoir can also be described and input to the model to help define the parameters of the desired power plant.

KEY ASSUMPTIONS

1) The resource type, whether it is hydrothermal, EGS, co-produced fluid with re-injection or other, is not specified in the model. However, the model does assume that the mass of the fluid brought up in the producer wells is equal to the mass of the fluid re-injected. Also, since the fluid is assumed to be re-injected, this excludes a broad swath of co-produced fluid from some oil and natural gas fields.

2) The power plant type–flash, binary, hybrid, etc. is assumed not to matter and is also not specified. In both conventional hydrothermal plants and EGS, the produced geofluid is re-injected into the reservoir, and some inventory tends to be lost, even in EGS where a binary plant is used. This latter condition is due to losses through other cracks and fissures that intersect the flow-path from the injector(s) to the producer(s), or bleed inventory away from the reservoir at the edges. However, since the re-injection flow rate is assumed equal to the production flow rate, this implies a binary plant. Furthermore, no geofluid phase change is assumed for the wells or reservoir.

3) For simplicity, it is assumed that the specific heat of the brine is constant throughout the plant, corresponding to the average temperature of the brine in the plant.

4) Reservoir geometry is assumed to be reasonably well described with a simple solid geometry; in this case a hybrid geometry between an elliptical disk and a rectangular slab. Currently the reservoir is assumed to be horizontal, although there are plans to allow various angles of inclination in future versions.

5) The reservoir is assumed to be essentially homogeneous and isotropic, and is modeled as a confined aquifer with constant bulk hydraulic conductivity throughout[6]. Thus, there is no need to define the fracture width, spacing or geometry. These will be incorporated in later versions.

6) All wells are assumed to penetrate vertically to the same depth and are of identical size. This assumption follows in part from the reservoir lying horizontally, and will likely change in the future.

7) Injector wells are assumed to be located a negligible distance from the power plant(s); this results in overland traveler lines associated only with production wells.

DISCUSSION

GSSM allows the analysis of the impact of manipulating various parameters of a geothermal power system on other parts of the system. The user can approach the problem from the perspective of desiring to build a plant of a specified size, and can then impose requirements on the reservoir to be created. This allows more of a scoping level type of analysis. Alternatively, the user can input known parameters of the reservoir and determine characteristics of the power plant. This approach lends itself to trade-off analyses.

There are a total of 31 input parameters for GSSM, broken down into five blocs: ambient conditions (one parameter), reservoir (nine parameters), power plant (13parameters), wells (seven parameters), and financial (one parameter).Note that the system is broken into four blocs for calculation purposes, but the wells are treated in generally the same way, with the difference being the inclusion of the overland traveling lines from the producers. Many of the input parameters are straightforward; those needing somewhat more explanation are described below.

Reservoir

Average geothermal gradient –the rate at which the temperature of the underlying rock increases with depth in units of °C/ km.

Reservoir "rectangularity" –refers to the degree to which the surface footprint of the reservoir tends toward rectangular rather than elliptical. This number is dimensionless and varies between 0 and 1, being a weighting factor used to calculate an average of the areas of a rectangle and an ellipse with the same length and width. Thus, the surface footprint is described as part ellipse, part rectangle, and can vary from a circle to a square. This allows somewhat more descriptiveness for the geometry of the reservoir. An example is shown in Figure 2.

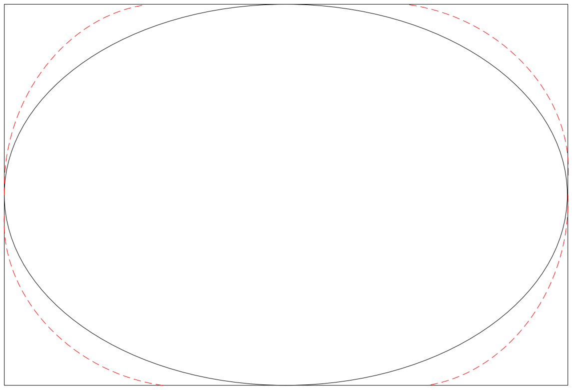


Figure 2: Example of ellipse with approximately 1/3 rectangularity (red dashed lines) showing its circumscribed ellipse and the rectangle which inscribes it

Portion of reservoir Energy Remaining if Extraction is Complete – the remaining portion of exergy in the reservoir after the desired amount of energy is extracted.

Input - Power Plant

Reject ΔT above ambient –the excess temperature relative to ambient at which the power plant rejects waste heat.

Efficiency coefficient –the fraction of Carnot efficiency at which the power plant actually operates.

Total dissolved solids - start up and finish are the amounts, in ppm, of dissolved formation and other material traveling in the geothermal fluid at the beginning and end of plant life.

Specific gravity adjustment - start up and finish represents the effects on the geothermal brine for such measures as brine density, viscosity, etc.

Lifetime average capacity factor – the ratio of the actual total energy produced by the plant over the rated lifetime to the total energy that could have been produced had the plant been running at full rated capacity continuously over its lifetime, this is a dimensionless number.

Efficiency coefficient – this dimensionless number is the proportion of the Carnot efficiency actually achieved by the plant.

Input - Wells

Brine-well heat loss coefficient –a lumped parameter to describe the heat lost by the geothermal brine in transit from the reservoir to the power plant. It is estimated here as a simple proportionality constant relating the distance traveled by the brine to the plant to the temperature decrease it experiences. It is not a physics-based parameter because there is no accounting for the differences between the well casing temperature and the free stream fluid temperature, not between the top and bottom of the well. It is intended to provide a somewhat more realistic description than simply assuming the plant inlet sees the bottom-hole temperature; units are in °C/m.

Fraction of length for production liner 1 - the fraction of the well that is of the widest diameter, Production liner 2 is the intermediate section diameter.

Input - Financial

Assumed lifetime average cost per kWh is a simple measure to convert plant output to financial return. It is intended only as a benchmark.

There are 33 outputs, although several of these are expressed in multiple different units so that there are 41 output lines in all. Most of these are self-explanatory. Others are described below.

Output – Reservoir

Initial reservoir temperature –the product of the well depth and the average geothermal gradient, units are in °C.

Final reservoir (abandonment) temperature –the lowest temperature reached by the reservoir just before that reservoir is abandoned, units are in °C. It is calculated from the initial reservoir temperature and the portion of energy remaining after extraction from the inputs, and has an error flag built in case this calculation goes below the re-injection temperature.

Extractable Initial Reservoir Energy Content - the amount of thermal energy that can be extracted from the reservoir based on specific heat, reservoir mass, and the difference between the initial and final reservoir temperatures.

Total Thermal Energy Extracted over Planned Lifetime of Plant - the total energy that is actually extracted from the reservoir over the course of the plant life. This is set to flag an error message if this value exceeds the Extractable Initial Reservoir Energy Content, above.

Output - Power Plant

Essentially all of the power plant output parameters are self-explanatory. Most are calculated at start up and finish to account for the effect of the changing temperature of the reservoir over the course of the plant life.

Time to complete extraction is the time it would hypothetically take if the reservoir were allowed to run all the way down to the final temperature. This must always be greater than or equal to the inputted planned plant life parameter.

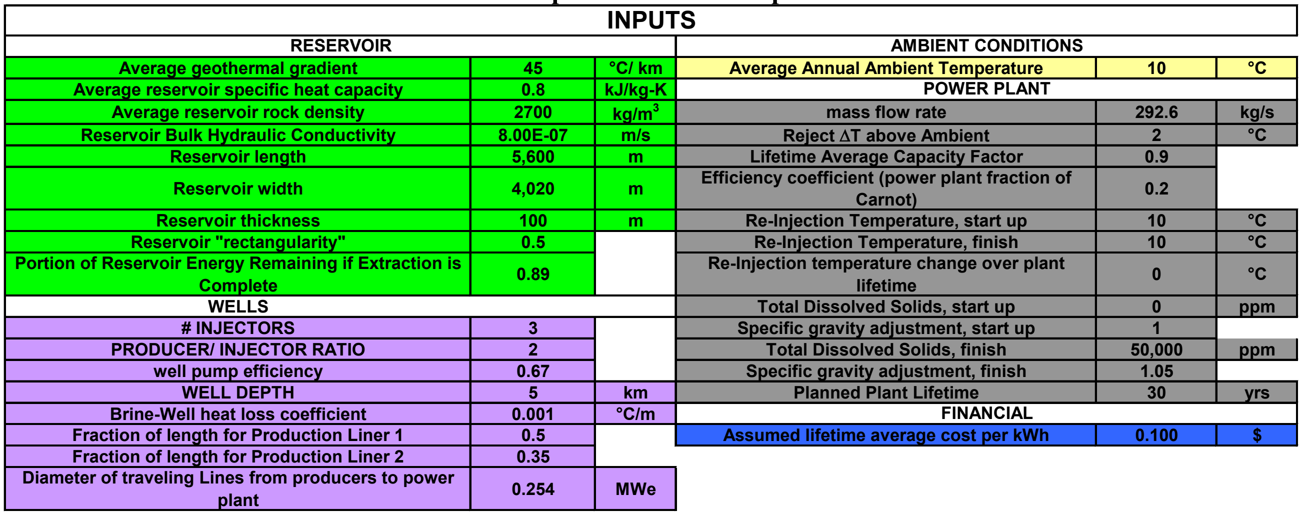
Output - Wells

The length of production liner 3 is calculated from the remaining portion of the well depth that is not taken up by liners 1 and 2.

Distance from producers to power plant - represents a compromise for a very complicated well spacing scheme. It is equal to the distance between foci of the ellipse in the case of one producer and one injector, half that if there are two producers per injector. In cases where there are more than two producers, calculations pertaining to wellfield layout were much more difficult to contend with. Even with the simplifying assumptions that all wells penetrate vertically and to the same depth, a great deal depends on the positions of the wells relative to one another, and there are far too many ways that multiple wells can be arranged for a given number of wells and a given surface footprint. Several approaches were attempted, including tessellation of a surface with regular polygons. In the end, a simple scheme was adopted based on the average footprint area per well and the perimeter of the surface footprint.

Well catchment facing represents the flow width through the reservoir (as it is modeled as a confined aquifer). It is normal to the flow direction and is set equal to four times the square root of the average surface (footprint) area per producer.

Table 1: Inputs for a 20 MWe plant



INPUTS					
RESERVOIR			AMBIENT CONDITIONS		
Average geothermal gradient	45	°C/ km	Average Annual Ambient Temperature	10	°C
Average reservoir specific heat capacity	0.8	kJ/kg-K	POWER PLANT		
Average reservoir rock density	2700	kg/m^3	mass flow rate	292.6	kg/s
Reservoir Bulk Hydraulic Conductivity	8.00E-07	m/s	Reject ΔT above Ambient	2	°C
Reservoir length	5,600	m	Lifetime Average Capacity Factor	0.9	
Reservoir width	4,020	m	Efficiency coefficient (power plant fraction of Carnot)	0.2	
Reservoir thickness	100	m	Re-Injection Temperature, start up	10	°C
Reservoir "rectangularity"	0.5		Re-Injection Temperature, finish	10	°C
Portion of Reservoir Energy Remaining if Extraction is Complete	0.89		Re-Injection temperature change over plant lifetime	0	°C
WELLS			Total Dissolved Solids, start up	0	ppm
# INJECTORS	3		Specific gravity adjustment, start up	1	
PRODUCER/ INJECTOR RATIO	2		Total Dissolved Solids, finish	50,000	ppm
well pump efficiency	0.67		Specific gravity adjustment, finish	1.05	
WELL DEPTH	5	km	Planned Plant Lifetime	30	yrs
Brine-Well heat loss coefficient	0.001	°C/m	FINANCIAL		
Fraction of length for Production Liner 1	0.5		Assumed lifetime average cost per kWh	0.100	$
Fraction of length for Production Liner 2	0.35				
Diameter of traveling Lines from producers to power plant	0.254	MWe			

In all well calculations, Reynolds numbers and friction factors (the latter from Petukhov) were calculated for each section.[5] Head losses and concomitant power losses were calculated. The same was done for the overland travelers. The head loss experienced by the geothermal fluid as it crossed the reservoir was calculated from Darcy's Law.[6]

Output - Financial

Well optimization - the geometric mean of the total return of the plant over its lifetime and the average total return per well. Since the total return will generally increase with the number of wells drilled, this provides a means of finding an optimum number of wells to drill, since real wells represent a significant investment and drive a significant portion of power plant cost.

Earlier versions of GSSM specified the size of the power plant as an input variable. This has been removed and now the power output appears only as an output variable. Also, drawdown has been removed as an input variable. It has been replaced with the related variable Portion of Reservoir Energy Remaining if Extraction is Complete. A brief example of the use of GSSM follows.

Example

A 20 MWe plant is considered. It is desired to find the effect of varying the flow rate on the average lifetime output and total return. The input as shown in Table 1.

In the base case, where the plant is a nominal 20 MWe, the output looks like Table 2.

Table 2: Outputs for a 20 MWe plant

OUTPUTS					
RESERVOIR			POWER PLANT		
Initial Reservoir Temperature	225	°C	Carnot efficiency, start up	42.18%	
Final Reservoir Temperature	170.2	°C	Carnot efficiency, finish	34.95%	
Ratio of minor:major axes	0.718		Plant thermal efficiency, start up	8.44%	
Distance between Foci	3,899	m	Plant thermal efficiency, finish	6.99%	
Area of Surface Footprint of Reservoir	20,096,442	m^2	Plant Output, start up	20.384	MWe
	20.0964	km^2	Plant Output, finish	5.451	MWe
Reservoir Volume	2,009,644,173	m^3	Plant Output, end of planned lifetime	19.617	MWe
	2.010	km^3	Plant Output, average over planned lifetime	20.000	MWe
Total Initial Reservoir Energy Content (relative to surface)	9.333E+14	kJ	TOTAL ELECTRIC ENERGY PRODUCED	540.0	MW-yrs
	2.592E+11	kW-hrs	Time to complete extraction	583.51	years
	29,573.8	MW-yrs	WELLS		
Extractable Initial Reservoir Energy Content	2.379E+14	kJ	# PRODUCERS	6	
	6.607E+10	kW-hrs	TOTAL # WELLS	9	
	7,537.4	MW-yrs	Distance from producers to power plant	1830	m
Total Thermal Energy Extracted over Planned Lifetime of Plant	7,001.5	MW-yrs	Fraction of length for Production Liner 3	0.15	
	6.138E+10	kW-hrs	Length of Production Liner 1	2,500	m
	2.210E+14	kJ	Length of Production Liner 2	1,750	m
Approach to complete extraction	92.89%		Length of Production Liner 3	750	m
FINANCIAL			Well catchment facing ('width')	7,321	m
Total Return over planned life of plant	$473,373,837	$			
Average annual return	$15,779,128	$			
Lifetime: extraction time ratio	5.1%				
Produced: extractable energy ratio	7.2%				
WELL OPTIMIZATION	$157,791,279	$			

GSSM allows us to examine the impact of varying input parameters on this base case. Figure 3 graphically shows the impact of flow rate on the average power delivered over the lifetime of the plant and the well optimization parameter. Calculations of the correlation coefficients shows that these are each actually sections of parabolas rather than straight lines. Note that this plant was designed such that the flow rate is at a maximum when it is producing 20 MWe. If the flow rate is raised even slightly, the Power Unsustainable under Given Parameters error message will appear since the lifetime energy extraction exceeds the Extractable Initial Reservoir Energy Content.

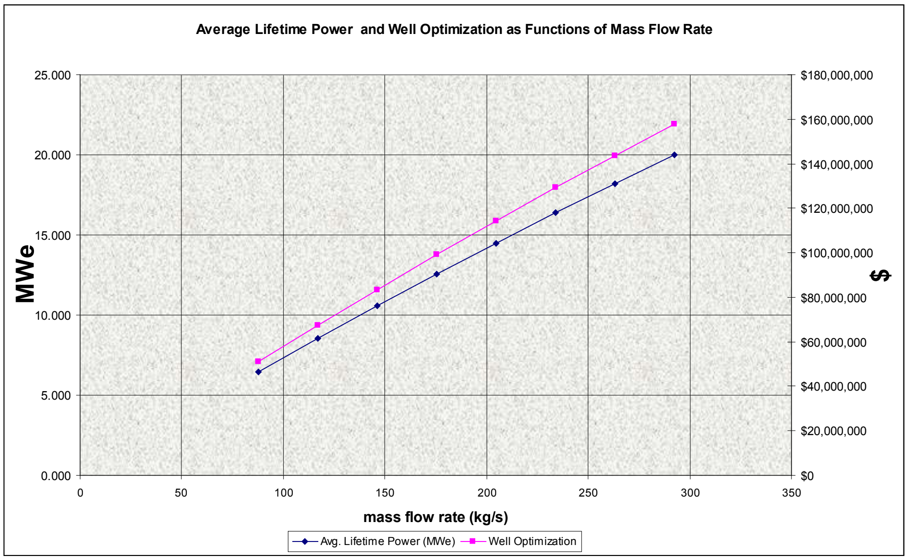


Figure 3: Average Lifetime Power and Well Optimization as Functions of Mass Flow Rate

Figure 4 shows the well optimization parameter and the plant power output as functions of the number of injector wells and producer to injector ratio. In contrast to the nearly linear relationship with flow rate, the optimizer clearly has a maximum at 2, from where it then decreases. However, if we look at the power output corresponding to the number of injectors, we see that the power production is clearly below its maximum. This is especially true in the case of the 1:1 producer-to-injector ratio. This would indicate that the design point for the best return on investment may not be 20 MWe with six producers and three injectors, but rather 18 MWe with three producers and two injectors. At the very least, it indicates there may be cause for reconsideration.

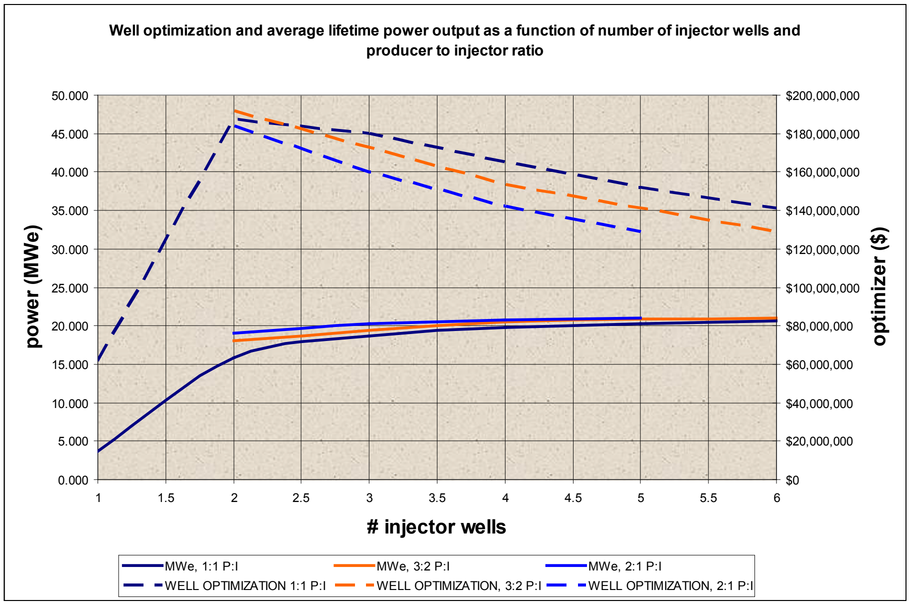


Figure 4: Power plant output and well optimization

CONCLUSION

GSSM is a product of DOE systems integration activities at NREL and is still a work in progress. It is intended for internal use, although this could conceivably change. When completed, it will be used to provide DOE with various scenarios to aid in making programmatic decisions.

Early efforts in the development of GSSM have already yielded some interesting results. However, because of the sheer number of variables, even with a large number of simplifying assumptions, there are no unique solutions. Nevertheless, improvements over earlier versions have been seen. Most notably, the reservoir's characteristics can now dictate the power plant that is built, which is a more accurate reflection of reality.

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14. **ABSTRACT** *(Maximum 200 Words)*

This paper discusses further developments and refinements for the uses of the Geothermal System Scoping Model in an effort to provide a means for performing a variety of trade-off analyses of surface and subsurface parameters, sensitivity analyses, and other systems engineering studies in order to better inform R&D direction and investment for the development of geothermal power into a major contributor to the U.S. energy supply.

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