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A HIGH LEVEL GEOTHERMAL SYSTEM SCOPING MODEL: A FIRST STEP TOWARD ENHANCED GEOTHERMAL SYSTEMS ENGINEERING

Mark Antkowiak[1], Neil K. Snyder[1] and Thomas S. Lowry[2]

1 National Renewable Energy Laboratory
1617 Cole Blvd.
Golden, CO 80401, USA
E-mail: Mark.Antkowiak@nrel.gov

Sandia National Laboratories, Albuquerque, NM
P.O. Box 5800 MS 1137
Albuquerque, NM 87185, USA

ABSTRACT

Within the field of geothermal power, the fields of well construction and engineering, power plant construction and engineering, and reservoir engineering often proceed independently of one another, and progress and results from one area do not necessarily inform the activities in another. Yet in any geothermal power plant, the surface facility interacts with the wells, and the wells interact with the reservoir, so clearly there is also an interaction between the power plant and the reservoir that is mediated by the wells.

These areas need to be integrated in order to make enhanced (or engineered) geothermal systems (EGS) a technical and an economic reality. In a collaborative effort between the National Renewable Energy Laboratory (NREL) and Sandia National Laboratories (SNL), a high –level model is under development that uses a lumped-parameter approach to examine the interplay among the several subsystems of a putative geothermal system– power plant, wells, and reservoir. The goal of this effort is to provide a basis for performing a variety of trade-off analyses and systems engineering studies in order to better inform R&D direction and investment for geothermal systems. This effort complements activities ongoing at SNL to develop a more detailed model of heat and mass transfer within the reservoir and to more fully describe geothermal systems dynamics..

INTRODUCTION

Recent years have seen a marked increase in interest and investment in geothermal power. This interest has in part been sparked by the publication of the seminal MIT study sponsored by the U.S. Department of Energy (DOE), *The Future of Geothermal Energy* (MIT, 2006), which describes enhanced, or engineered, geothermal systems (EGS).[i] In conventional geothermal, or hydrothermal, systems, there is a natural occurrence of highly fractured or otherwise permeable hot rock relatively close to the surface (typically less than 1500 m) that comes into contact with water from an overlying aquifer or recharge area, allowing water to percolate through the fractures or pore spaces and become heated. This hot water is then brought to the surface and passed through a power plant, which extracts this heat and converts it to electric power. In the case of a binary type power plant, the geofluid is re-injected into the reservoir. In a flash type plant, the geofluid is the working fluid. It is flashed to steam and expanded through a turbine, then passed through a condensing/cooling system where some of the inventory is lost to evaporation. The remaining fluid is re-injected into the reservoir.

In EGS, the naturally occurring hot rock is either does not contain enough water, is impermeable, or both, and generally lies at greater depth than is typical of hydrothermal systems. Fracturing of this rock and the introduction of a geofluid (assuming water initially, but later other fluids may be used, such as CO_2) is necessary to enable the extraction of useful heat energy. Again, the fluid is passed through a power plant on the surface and subsequently re-injected.

The purpose of this work is to develop a simple, flexible, high level geothermal systems model to enable the US Department of Energy's Geothermal Technologies Program (GTP) to conduct trade studies and sensitivity analyses among the various components and parameters of a geothermal power station. For example, a question 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?" This Geothermal Systems Scoping Model (GSSM), still under development, can help answer questions such as this, and can inform decisions on prioritization of research areas and selection of technical targets in order to achieve program and national goals. This work will dovetail with and to some extent, be incorporated into, complimentary work being performed at Sandia National Laboratories.

In order to construct this model, the broad parameters of a geothermal power plant design are outlined using a readily accessible spreadsheet program (MS Excel) in a so-called 'black box' approach, which makes extensive use of lumped parameters. The individual black boxes – the surface facility, the well system, and reservoir, are interconnected but most engineering details of each are not specified, the interactions among them are what's important.

In this sense, GSSM is more concerned with interface engineering among the various subsystems. Parameters are lumped as much as possible within the black boxes – the entire surface facility is characterized by a small handful of parameters; reservoir geometry is assumed to have a hybrid elliptical-rectangular surface footprint but overall shape is still determined by the user; wells are modeled with uniform diameter and are assumed vertical. 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 in order to identify those areas where the most can be gained from R&D investment. It is thus not a process model such as ASPEN Plus, or a replacement for programs such as the Geothermal Energy Techno-Economic Model (GETEM), although there are some overlaps, and it is hoped that the work will eventually be able to dovetail with these or similar programs. These two particular examples interact easily with Excel, which is part of the motivation for using this software package.

DEFINITIONS AND ASSUMPTIONS

The 'black boxes' indicated previously are briefly described below. This is followed by a discussion of the various simplifying assumptions

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 system (see below).

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 assumed to be withdrawn uniformly from the entire volume as well.

Wells

This includes all injector and producer wells, plus any additional pumping required in order to provide motive power to the fluid to pass it though through the wells and reservoir. Pumping power required to move fluid through the plant is subsumed in the power plant and is not included here.

The well subsystem is comprised of two portions: that portion of the geothermal fluid circuit between the plant outlet (at the condenser) and the bottom(s) of the injector well(s), and that portion between the bottom(s) of the producer(s) and the plant inlet (at the vaporizer). Thus the overland portion of the system piping connecting the wells to the power plant is included here.

These boxes are conceptually arranged as diagramed in Figure 1. In this configuration, either the power plant can be selected to impose requirements on the reservoir, or the reservoir can be selected to impose constraints on the power plant that can be built. The requirements and the constraints are mediated by the wells. The contents of the black boxes are shown in Figure 2.

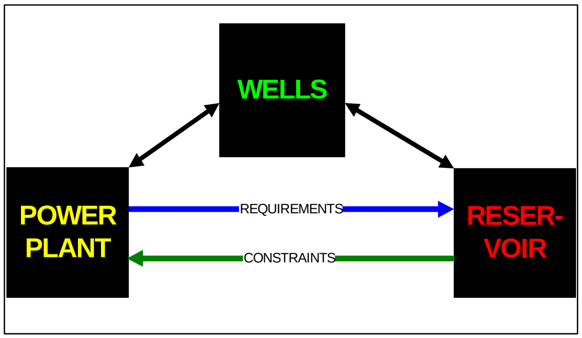

Figure 1: Conceptual Diagram of a Geothermal System

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constraints on the power plant that can be built. The requirements and the constraints are mediated by the wells. The contents of the black boxes are shown in Figure 2.

Thus, GSSM can be used to determine the general requirements that a potential reservoir formation must meet. This formation can then be subsequently engineered to try to fulfill the requirements. In the end, the actual reservoir created imposes constraints on the power plant that can be built.

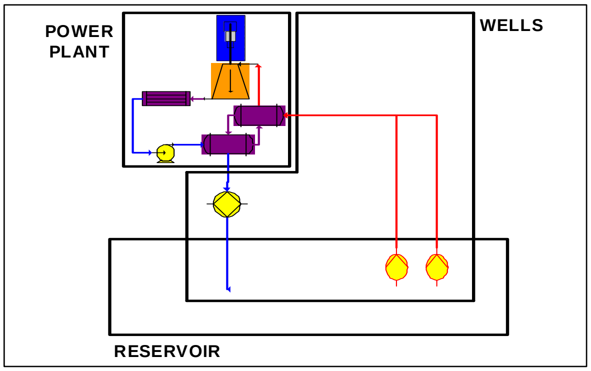

Figure 2: Geothermal "Black Boxes"

Key Assumptions

1) The resource type, whether it is hydrothermal, EGS, co-produced fluid with re-injection or other, is assumed not to matter and is not specified in the model.

2) In the current form of the model, it is assumed that the mass of fluid brought up in the producer wells is equal to the amount re-injected.

3) 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, and also implies that the resource may not be co-production fluid since there would otherwise be an expected reduction in mass flow rate as the primary resource of interest, oil or natural gas, is extracted from the flow. A similar argument applies for mineral extraction schemes as well.

4) The brine specific heat capacity is assumed to be 95% that of pure H_2O, or roughly the equivalent of seawater, and its specific gravity is assumed to be 1.05. Also, viscosity is assumed to be 1.05 times that of pure water to account for ionic effects arising from mineral dissolution that may tend to resist shear.

   These simplifications provide a bit more accuracy than assuming pure water, and at the same time eliminate complex calculations relating to a) the differing solubility of minerals at different temperature and pressure conditions at varying locations within the system, and b) variations in geochemistry expected in the varying mineral compositions of different reservoir formations.

5) 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.

6) 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.

7) The reservoir is assumed to be essentially homogeneous and isotropic, and is modeled as a confined aquifer with constant bulk hydraulic conductivity throughout (Fetter, 1988). Thus, there is no need to define the fracture width, spacing or geometry.

8) Currently, all wells are assumed to penetrate vertically to the same depth and to be of uniform diameter. This latter assumption will tend to over-estimate the head loss due to friction as well as the concomitant power loss.

9) Injector wells are assumed to be located a negligible distance from the power plant(s); flow from the producer wells is assumed to travel through overland pipes of the same smaller diameter as that used for the wells to the power plant(s). Again, this will tend to over-estimate the head loss due to friction as well as the concomitant power loss.

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 types of analyses. There are two input screens to accommodate this two-pronged approach.

Table 1: GSSM Input Parameters

average annual ambient temperature	reject ΔT above ambient
drawdown rate	lifetime average capacity factor
average geothermal gradient	efficiency coefficient
average reservoir specific heat capacity	re-injection temperature, start-up
average reservoir rock density	re-injection temperature change over plant lifetime
ratio of minor/major axis	# injectors
bulk hydraulic conductivity	producer/ injector ratio
reservoir length	well pump efficiency
reservoir width	well depth
reservoir thickness	brine-well heat loss coefficient, injector diameter
reservoir ""rectangularity"	producer diameter
plant design output	reject ΔT above ambient
pinch point ΔT at vaporizer	lifetime average cost per kWh

In this type of arrangement, the inputs must necessarily differ to some extent. On the reservoir specification page, the user inputs 26 parameters of the system and can then assess the effects on 20 different output parameters. On the power plant specification page, the user inputs 23 parameters of the system and has 10 different output parameters.

The reservoir specification page has input parameters as shown in Table 1. Most of these are self-explanatory. Others are described below.

Average Annual Ambient Temperature – this is the year-round, diurnal average temperature of the power plant's surroundings, to which it must reject waste heat;

Drawdown Rate – drawdown of the heat in the reservoir is formulated as an exponential decay function and this lumped parameter is the decay constant, with units of yr^{-1};

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

Ratio of minor/major axis – for purely elliptical footprints this is self-explanatory. For rectangular footprints, this is simply the ratio of the width to the length;

Reservoir rectangularity – this term refers to the degree to which the surface footprint of the reservoir tends towards 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 area 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.

Plant design output – this is the nameplate rating of the power plant, in MWe;

Pinch point ΔT at vaporizer – the difference between the maximum temperature of the working fluid and the maximum temperature of the geothermal brine, units are in °C;

Reject ΔT above ambient the difference between the ambient temperature and the reject temperature, units are in °C;

Lifetime average capacity factor – this is 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 is the proportion of the Carnot efficiency actually achieved by the plant, this is a dimensionless number;

Re-injection temperature, start up – this is the temperature at which the brine exits the plant and is re-injected into the injection wells near the beginning of the plant lifetime, units are in °C. This temperature slowly decreases over the life of the plant.

Re-injection temperature change over plant lifetime – this is the difference between the re-injection temperature near the beginning of the plant life and the re-injection temperature near the end, units are in °C;

Producer/injector ratio – ratio of producers to injectors. As an input parameter, it determines the number of producers when combined with the number of injectors, with appropriate rounding. It is also re-calculated as an output parameter when a user is using the power plant specifications to determine the reservoir characteristics..

Brine-well heat loss coefficient – this is 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, units are in °C/m;

Injector diameter, producer diameter – these are the minimum diameters of the wells in question, in meters. All injectors are assumed to be of the same diameter, as well as all of the producers.

Assumed lifetime average cost per kWh – this is a high level estimator used for general cost comparisons only, and in no way should be construed as a predictor. Its units are dollars. It is intended as a means to estimate the lifetime gross return from the particular plant configuration in question.

The power plant specification page does not specify average geothermal gradient, reservoir length, reservoir width, reservoir thickness, reservoir rectangularity, or reject ΔT above ambient. Instead, it specifies initial reservoir temperature, ratio of height to semi-minor axis (it assumes an elliptical footprint), and plant design life.

The output parameters for the reservoir specification page are shown in Table 2. Most of these are self-explanatory. Others are described below.

Initial reservoir temperature – this is calculated from the well depth and the average geothermal gradient, units are in °C;

Final reservoir (abandonment) temperature – this is the lowest temperature reached by the reservoir just before that reservoir is abandoned, units are in °C;

Percentage of available energy used – this is the portion of the heat energy available in the reservoir (relative to the surroundings of the surface facility) that is actually produced as electricity;

Gross return over plant lifetime – this is a guideline for economic purposes. It is the product of the total energy produced over the plant life and the average price per kW, units are dollars;

Average annual gross return – the preceding divided by the lifetime of the plant in years;

Optimizer parameter – this is a variable for use in economic decisions, despite the unusual units of GWh^2. It is the total energy produced over the life of the plant times the average energy per well. Since the total energy output 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.

The power plant specification page lacks nine of the outputs of the reservoir specification page. These are power plant reject temperature, initial reservoir temperature, final reservoir (abandonment) temperature, ratio of height to minor axis, net plant output, average percent of rated capacity, plant lifetime, percentage of available energy used, and average annual gross return.

Generally, the reservoir specifications are the same as or an improvement over the power plant specifications. The reservoir inputs are more aligned with measured parameters, rather than assigned. This approach also enables the use of the output of more sophisticated models, such as the EGS Systems Dynamics Model being developed by Sandia National Laboratories, that can model a reservoir more effectively, as input for GSSM. At the same time, GSSM can also provide valuable in put to models such as these (Lowry et al., 2010).

Table 2: GSSM Output Parameters

power plant reject temperature	total energy delivered over plant lifetime
initial reservoir temperature, initial reservoir temperature	percentage of available energy used
final reservoir (abandonment) temperature	lifetime average net plant efficiency
ratio of height to minor axis	30 year average power output per well drilled
net plant output, start up	# producers
net plant output, retirement	total # wells
net plant output (average percent of rated capacity)	gross return over plant lifetime
plant lifetime	average annual gross return
percent decrease in plant output over lifetime	optimizer parameter

In addition to the preceding, there are numerous calculations that are carried out in the background of GSSM. These are calculations for the fluid properties of density, specific heat capacity and viscosity for use in hydraulics calculations. The fluid properties determined are for water over a range of temperatures, with simple adjustments as noted previously. These properties are calculated from correlations developed from tabulated data from a standard heat transfer text (Incropera, and DeWitt, 1996). All values are based on the average temperature of the fluid in the portion of the geothermal system under consideration.

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.

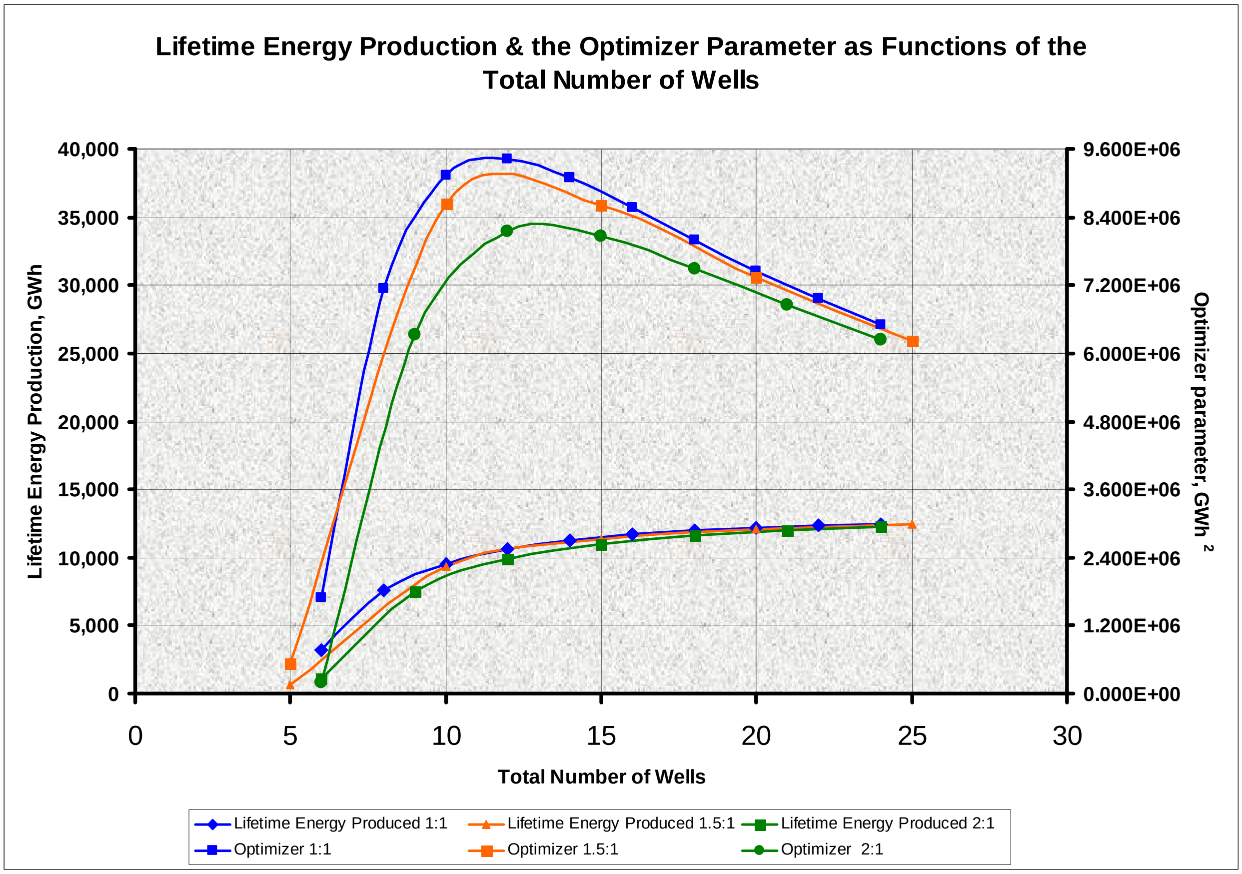

Figure 3: Example of GSSM Preliminary Results Showing Lifetime Energy Production

EXAMPLES

A 50 MWe nameplate capacity power plant is considered. The resource temperature is 195 C and its depth is 5000 m. Injector and producer wells have diameter of 10” (0.254 m)and the plant is assumed to operate at 1/3 of Carnot efficiency. Re-injection temperature is 80 C for the life of the plant. The drawdown rate is set at 0.0013 yr-1 and the ambient is 20 C. The reservoir is elliptical with a major axis of 16.16 km and a minor axis of 11.43 km. It is 286 m thick.

Figure 3 shows the total energy produced over the life of the plant and the optimizer parameter as functions of the total number of wells drilled and the producer to injector ratio.

These results show that the best producer to injector ratio under these assumptions is 1:1. It may well be that the results would differ significantly if the injectors were of larger diameter than the producers, or if both were sufficiently large in diameter that friction head losses are negligible, for example.

In a second example, most input parameters are held constant and the optimum total number of wells drilled and total lifetime gross returns are calculated as functions of net power plant efficiency by varying the portion of Carnot efficiency achieved by the plant for several different producer to injector ratios. The results are shown in Figure 4.

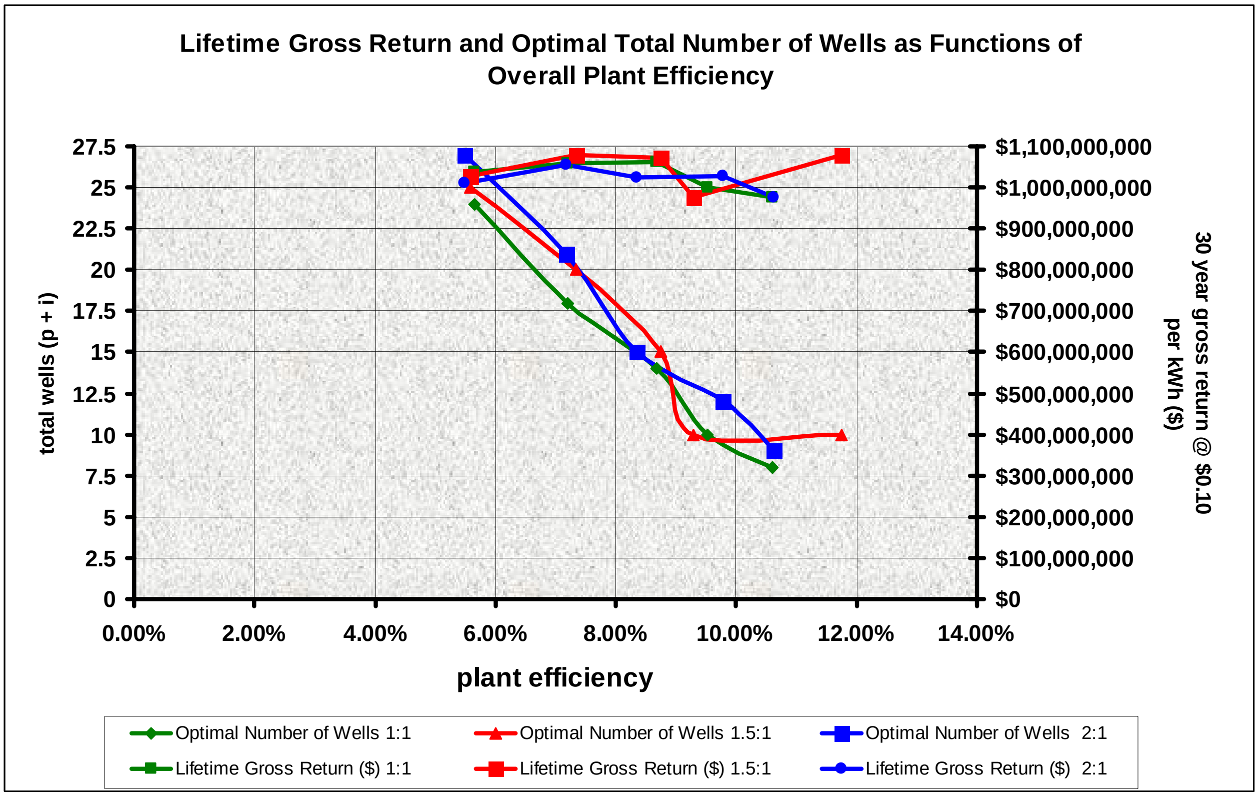

Figure 4: Example of GSSM Preliminary Results Showing Optimal Number of Wells to Drill

FUTURE WORK

In the future, additional features will be added to GSSM, which is still in early stages of development. These features include, but are not limited to partial automation (macros), brine chemistry dependent viscosity, density, heat capacity, better friction factor hydraulics calculations using surface roughness, better well models, accounting for inventory loss (leakage, extraction, flash)) and the effects of make-up water, better representations of reservoirs (hydraulic conductivity, heat transfer, variables, etc.), and well heat loss using actual physics – heat transfer dependent upon Reynolds & Prandtl numbers, etc. column.

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