Review of Past Geothermal Energy Return on Investment Analyses

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ABSTRACT

Energy Return On Investment (EROI) is an important figure of merit for assessing the viability of energy alternatives. EROI analyses of geothermal energy are either out of date or presented online with little supporting documentation. Often comparisons of energy systems inappropriately use "efficiency" when EROI would be more appropriate. For geothermal electric power generation, EROI is determined by the electric energy delivered to the consumer compared to the energy consumed to build, operate, and decommission the facility.

Determination of EROI depends upon several factors. First is the input energy embodied into the system – the available energy needed to make, operate, and decommission a product or system. Two approaches that are used in determining embodied energy, Input/Output Analysis and Process Energy Analysis, are reviewed. Also, critical to determining EROI is the system boundaries and value of the energy – heat is not as valuable as electrical energy. The concept of closing the loop is a useful way of assessing if boundaries and the value of energy have been addressed adequately.

The methodology and results of past geothermal EROI studies are reviewed and issues or problems conducting and interpreting EROI analyses are discussed. The validity of past geothermal EROI estimates is investigated by spot checking the major energy inputs into constructing a geothermal wellfield. A preliminary, update to EROI for geothermal power production is presented and applied to understanding future of geothermal development.

Introduction

EROI analysis is also referred to as energy return on *energy* investment, energy return, energy ratio, net energy, or energy payback ratio. The primary reason for conducting EROI analyses is to identify technologies that are potentially net energy consumers rather than producers. Standard economic analysis does not necessarily distinguish between net energy consumers and producers especially when there are subsidies.

A geothermal power production facility (Figure 1) involves four energy streams: 1) the heat extracted from the reservoir, 2) the heat rejected to the atmosphere, 3) the energy to construct, operate, and decommission the facility, and 4) the electrical energy delivered to the customer. The heat flowing from the reservoir and the heat rejected to the atmosphere are significant in determining the efficiency of the system, but are not explicit factors in EROI. Efficiency is the ratio of the energy delivered to the customer to the energy extracted from the earth. Whereas, EROI is the ratio of the energy delivered to the consumer to the energy consumed to build, operate, and decommission the facility.

To be meaningful EROI must consider the value of the input and output energies. Not all energy is of equal value in its usefulness and/or ability to do work. Thus, studies of energy alternatives need to consider the value of the input energy compared to the

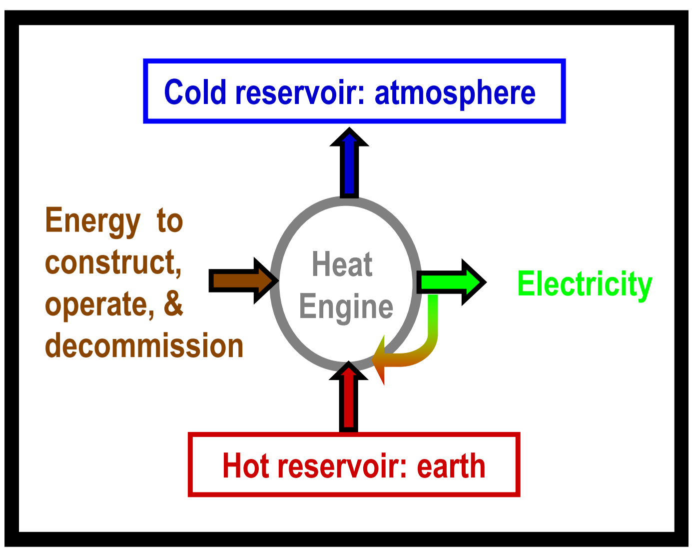

Figure 1. Geothermal heat engine converting raw materials and heat from the earth into electricity.

value of the output energy. Energy in a geothermal reservoir or the atmosphere is of no particular value unless it is incorporated into some process such as producing electricity. Energy embodied into the fuel and raw materials consumed to build, operate, and decommission the facility (steel, cement, fuel, chemicals, etc.) has inherent value. That is, it can be used for food production, shelter, transportation, etc. One way the value of energy can formally be accounted for is using available free energy or exergy (Patzek, 2004). In addition to the ability to do work, other significant value metrics for comparing energy alternatives include portability and storability. For example the chemical energy contained in liquid fuel is highly valued, not just for its ability to do work, but also for its portability and storability.

One way to account for value in assessing the EROI of a geothermal power production facility is to convert all energies to electricity. That is, express the input energy embodied into the materials used to construct the plant in terms of how much electrical energy would be required to manufacture the steel, cement, etc. This leads to the concept of closing the loop. That is, using the output of existing geothermal power production to produce the materials (provide the capital energy investment) for the next generation geothermal power production facility. Thus closing the loop provides a check on whether the boundaries of the system have been drawn adequately.

Methodology

Process Energy Analysis

Process analysis of embodied energy[1] is a detailed bookkeeping exercise summing energy inputs from raw material mining through the chain of manufacturing to finished products. For example, this would include accounting for the energy of mining raw materials (iron ore, coal, etc.), transporting the raw materials to the foundry, forging the steel, machining the pipe, shipping the resulting casing to the well construction location, and running the casing into the hole. The energy contained in the material as well as that consumed at each stage is "embodied" into the materials at the next stage. That is, at any given stage the embodied energy is the sum of all the upstream energies needed to manufacture and deliver the product. The second law of thermodynamics dictates that the embodied energy is always more than the energy "contained" in the final product. As an example, for diesel fuel which is an energy dense and highly valued product, the embodied energy is ~20% more than the energy released by burning the fuel (Brinkman, 2005). The extra 20% accounts for the energy needed to produce, refine, and deliver the fuel.

Process analysis of the embodied energy of a product requires considerable detailed work. If the upstream material and energy balance data needed for process analysis does not exist, it must be determined as part of calculating EROI. Thus in the 1970's only a few process analyses of embodied energy were performed. Rather input/output analysis was used to estimate embodied energy needed to construct, operate, and decommission a geothermal power production facility.

Input/Output Analysis of Embodied Energy

The input/output approach to calculating EROI relies on economic data. Material quantities and energy data are typically only input into the analysis for primary energy sources such as coal, petroleum, hydroelectric, nuclear, etc.

The input/output analysis approach to determining EROI involves two steps. First economic data is used to calculate energy intensities (kJ/$) for each aggregated commodity of the economy. Monetary flows between economic sectors are assumed surrogates for material and burdened or embodied energy flows. That is, where energy or material flows are not know, monetary flow are put into the equations and it is assumed that the energy or material flows are proportional to the monetary flows. The entire countries' economy is represented by the following simultaneous equations (Bullard and Herendeen, 1975):

$$\sum_{i=1}^{N} e_i X_{i,j} + P_j = e_j O_j \quad , \tag{1}$$

where

$X_{i,j}$ is the transaction from sector *i* to sector *j*,
P_j is the energy input from the earth or sun and is non-zero only for primary energy sectors of the economy, e.g. coal, petroleum, hydroelectric, nuclear, etc.,
O_j is the total output of sector *j*, and
e_j is the embodied energy intensity per unit of $X_{i,j}$.

Expressed in matrix form the solution to equation 1 for the energy intensities is

$$e = P\left(X - O\right)^{-1} \tag{2}$$

An example of the application of this system of equations is provided in the appendix of Mansure and Blankenship (2010).

Once standard energy intensities are known, Input/Output Analysis of EROI starts with life-cycle cost analyses and multiplies cost categories by the energy intensities to get the embodied energy.

There are several inherent issues in using Input/Output Analysis energy intensities. Even if the economy is divided into a large number of segments (398 segments for Bullard and Herendeen's 1975 work), there is still significant aggregating of commodities; the resulting energy intensities are thus gross averages. It has been demonstrated that aggregating of comedies tends to minimize differences between energy intensities (Herendeen, 1981). The validity of monetary flows as surrogates for energy flows may vary from commodity to commodity and can only be assessed by Process Energy Analysis. Another concern is the representativeness of the aggregated commodities: for example is the energy intensity for cementing, presumably an aggregate derived from the building and construction industry, representative of well construction cementing? Further discussion of issues associated with Input/Output Analysis energy intensities can be found in Mansure and Blankenship (2010).

Past Geothermal EROI Analyses

EROI analyses of geothermal power production are either old enough that they need to be updated to current technology (Herendeen and Plant, 1979 a&b) or are presented online with little supporting documentation. For the wellfield, the starting point for Herendeen and Plant's work was cost data from a report by Republic Geothermal (1979), "Industrial Assessment of Drilling Completion and Workover Costs of the Well and Fracture Subsystems of Hot Dry Rock Geothermal Systems." While that report is mentioned in numerous publications, a copy or proper reference for that report has not been found. Herendeen and Plant's costs for the power plant were taken from an EPRI (1978) report on Heber. Herendeen and Plant used the "standard" approach (IFIAS, 1974) to determine embodied energy. The energy intensities they used are from Herendeen and Bullard (1974) and Bullard et al. (1978).

Herendeen and Plant's (1979a) results are summarized in Table 1. HDR refers to Hot Dry Rock, an early manifestation of what are Enhanced or Engineered Geothermal Systems (EGS). They also provide power-in and power-out vs. time curves that can be used to determine energy payback time (time after startup the facility must operate in order to pay back the energy invested). Payback time is also an important metric in assessing the viability of energy alternatives.

Table 1. EROI's calculated by Herendeen and Plant.

	EROI	EROI w/o silica treatment	Depth (km)
Liquid Dominated			
High turbine cost	4.3 ±1		
Low turbine cost	4.4 ±1		
HDR			
35°C/km	2.7 ±0.9	2.9	5.7[2]
45°C/km	3.4 ±1.0	3.8	4.4[2]
55°C/km	3.9 ±1.1	4.4	3.6[2]
Low Temp.	1.9 ±0.6		
"Best" case	13 ±3		
Geopressured	2.9 ±0.9		
Vapor Dominated	13 ±4		

Table 2. Herendeen and Plant's embodied energy for a 5.7 km EGS well.

	TJ/ well	% Input	% Output
Fuel	105	30.4%	10.5%
Rig Time	72	20.9%	7.2%
Well O&M	47	13.6%	4.7%
Power Plant	44	12.7%	4.4%
Casing	29	8.4%	2.9%
Cementing	13	3.8%	1.3%
Bit Cost	11	3.1%	1.1%
Pipelines	9	2.7%	0.9%
Other	15	4.4%	1.5%
Total	346	100.0%	34.4%

Table 3. Process analysis calculations of input energy for a 5.7 km EGS well compared to Herendeen and Plant's estimates.

	H&P (TJ)	Current (TJ)	FG (TJ)
Rig Fuel	105	54.2	18.4
Casing	28.9	35.7	40.6
Cementing	13.0	13.2	15.0
Pipelines	9.4	4.0[4]	

EORI is sensitive to the assumptions made during the analysis. Silica treatment costs are included in Herendeen and Plant's analysis because they used work on the Heber resource (EPRI 1978) as the cost basis for the power plant. Heber has a total dissolved solids content of 13,000 ppm. While long term, if they exist, geochemistry issues of EGS are yet to be determined, Heber (a hydrothermal resource) is probably not representative of EGS geochemistry. The third column of Table 1 shows the effect of removing silica treatment costs. For the balance of this paper, comparisons to Herendeen and Plant's work will be without silica treatment costs.

Table 2 shows the percentages of energy investment according to Herendeen and Plant for their 35°C/km EGS or 5.7 km well case. Percent input is the percent of the total energy needed to construct and operate the facility. Percent output is the percent of the energy delivered to the customer. The table shows that fuel (energy embodied in the diesel fuel used by the drilling rig) is the largest energy component followed next by rig time. (The meaning of energy associated with rig time is not clear but is calculated as rig costs multiplied by energy intensity, kJ's/$, for "new construction," which is an aggregate of construction industries, and applies presumably to drilling contractors. This is one example of the details of previous work that should be further investigated).

Assessment of Past Geothermal EROI

As a preliminary check on the well construction side of Herendeen and Plant's work, the energies embodied into the diesel fuel, casing, cementing, and wellfield pipelines have been estimated for an EGS well using the process analysis approach. The Appendix demonstrates this process for a 20,000 ft (6.1 km) well. The well plan used in the Appendix was chosen because it has been documented in detail in published reports (Polsky, 2008 and Polsky 2009). To compare to Herendeen and Plant's work, the casing design of the well in the Appendix was modified so that the well is 5.7 km deep. From the Appendix it is apparent that the most significant materials are fuel, steel, and cement. However, to compare to Herendeen and Plant's work, it is more convenient categorize the input energy invested as rig fuel, casing, well cementing,[3] and wellfield pipelines. Table 3 compares the embodied energies determined by Herendeen and Plant to those calculated for a 5.7 km deep well following the procedure described in the Appendix. The third column labeled FG is the numbers reported at the Stanford Geothermal Workshop (Mansure and Blankenship, 2010). That analysis used a well plan taken from work done for *The Future of Geothermal Energy* (MIT, 2006). The current work, as outlined in the Appendix, uses a leaner casing design; hence, less steel and cement than the well plan taken from work done for *The Future of Geothermal Energy*. However, the current analysis uses a larger rig, a top drive, and a higher fuel consumption rate; hence the higher fuel energy. Cost of these two well plans is not significantly different, but the strategy to minimize cost was different; in effect one minimized fuel, while the other minimized steel and cement. Such differences in strategy are one contribution to uncertainty/variation in energy invested in wellfield construction.

Current calculations of cementing and casing embodied energies agree reasonably well with Herendeen and Plant's work, especially considering their work is presumably based on smaller diameter wells, consistent with drilling practice in the 1970's. Detailed comparison with their work is difficult without the Republic Geothermal (1979) report.

The factor of ~2 times or more fuel in Herendeen and Plant's calculation than the current estimate is readily understood in terms of improved rate of penetration (ROP), bit life, and diesel generator efficiency. The impact of such improvements can be estimated based on a report by Cummings et al. (1979) which contains a table of data, "Range of values used for HDR drilling time estimates," taken from the Republic Geothermal work. Based on Cummings' table, to account for technology improvements Herendeen and Plant's fuel calculations need to be reduced by about 60%, enough to explain the lower fuel energies of current work. This one technical improvement is enough to increase the EROI of their 5.7 km well from 2.9 to 4.2.

A significant factor in determining EGS EROI is the well productivity. Herendeen and Plant used 20 well pairs for a 50 MWe power plant; that is, 2.5 MWe per production well. They assumed that after 5 years the temperature will decline sufficiently that the wells would need to be recompleted (restimulated). Figure 2 shows the effect of well productivity on the EROI for Herendeen and Plant's 5.7 km EGS case. The low end of the curves corresponds to 2.5 MWe per well. The high end, 6 MWe per well, was calculated using GETEM (Mines, 2008) assuming a 215°C reservoir and 80 kg/sec well flow rate. 215°C is the reservoir temperature assumed by Herendeen and Plant. 80 kg/sec is the high base case well flow rate in *The Future of Geothermal Energy* (MIT, 2006). The upper curve in Figure 2 is Herendeen and Plant's work revised to current technology fuel consumption, a 60% reduction in fuel consumption.

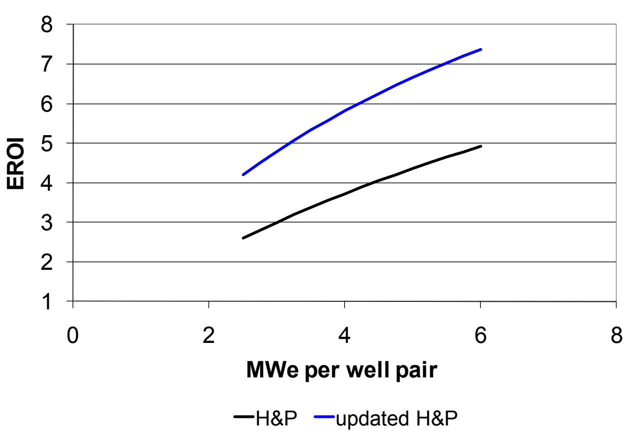

Figure 2. Herendeen and Plant EROI as a function of well productivity.

Other areas where technology has reduced the embodied energy include wellfield pipelines and the power plant. Table 3 indicates that the energy cost to construct the wellfield pipelines may be less than half that required in the 1970's. Herendeen and Plant estimated the energy embodied in construction and operation of the power plant to be 4.4% of the energy that can be produced (5.7 km case). Preliminary results of the Life Cycle Analysis (LCA) of geothermal power production being conducted by Argonne National Laboratory (Sullivan et al., 2010) indicate that the input energy embodied in the power plant may be as low as 1.4% of the produced energy. Thus the power plant is another area where technology improvements have reduced the energy investment needed to construct and operate an EGS power production facility.

Other factors that may change EROI include the strategy for replacing production as temperature declines and the embodied energy attributed to labor and services. Herendeen and Plant assume that declining production will be replaced by recompleting the wells via additional stimulation. They estimate the energy to restimulate the wells to be insignificant.[5] The viability of restimulation is unproven. In fact, from the *Future of Geothermal Energy* (MIT 2006), one would assume that after the temperature declines wells are abandoned. Since wellfield construction accounts for most of the energy investment, switching from recompletion to abandonment would result in a significant EROI penalty.

From Table 2 one sees that Rig Time and Wellfield O&M account for 21% and 14% of the energy investment respectively. Wellfield O&M is not defined in Herendeen and Plant's work and thus, without the Republic Geothermal (1979) report one cannot assess how much of this is materials and how much is services and labor, but the latter is probably substantial. Rig contractor costs are not primarily for materials and as noted in the Appendix the amortized energy embodied in the drilling rig and machinery is not substantial. One is left then with the conclusion that from 20% to 35% or more of the energy investment is for labor and service like functions. LCA's have typically not found labor and services to be a significant contributor to input energy (Wu et al., 2006). Thus, either major contributors to energy investment have been overestimated by Herendeen and Plant or the energy embodied in geothermal power production has a different distribution than other energy systems.

Recognizing the need to update Herendeen and Plant's work, it is still instructive to examine its implications by plotting their EGS EROI as a function of well depth (Figure 3). While there are substantial uncertainties with projections beyond the range of actual data, in this case below 5.7 km, note the figure shows that according to their calculations somewhere about 11 km the energy needed to construct and operate the facility exceeds the electric energy that can be produced. While the actual point where the EROI drops to 1 will change as better estimates of EROI are obtained, the curve leads to several significant conclusions. First, in estimating the EGS resource base, the depth below which the EROI is 1 should not be considered. As we seek new technologies

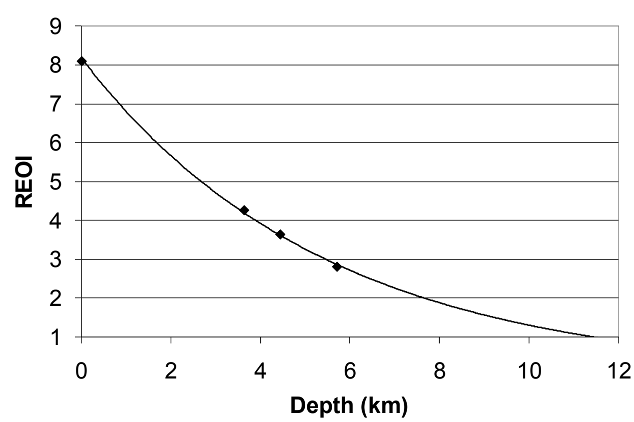

Figure 3. Herendeen and Plant's EGS EROI as a function of well depth[6].

to drill deep EGS wells, in addition to cost, consideration needs to be given to the energy needed to construct the well.

Progress

There are aspects of past analysis of geothermal power production EROI that merit further investigated if the background information can be located (e.g. Republic Geothermal 1979 report, details about energy intensities used, etc.). However, adequate information has been found to identify areas where technological improvements have reduced the energy investment necessary to build and operate an EGS power production facility: improved bit performance, reduced power plant embodied energy, and reduced wellfield pipelines embodied energy. Also EGS well productivity has improved since the 1970's, c.f. Fenton Hill vs. Soultz. Analysis of past work has identified significant energy drivers as well productivity, rig fuel, casing, cementing, wellfield pipelines, and the power plant. A robust approach for developing material inventories and embodied energy for the wellfield has been demonstrated (the Appendix). Thus, together with power plant data from Argonne National Laboratory's LCA, it will be possible to calculate an up-to-date EROI for EGS power production. However, significant issues remain: the impact of labor and services, wellfield productivity, and how depleted production will be replaced.

Closing Remarks

Geothermal resources are much simpler than many of the other energy alternatives (e.g., they don't have the complexity of soil depletion of bio-fuels, they integrate into the existing infrastructure without storage, they don't produce long term hazardous waste, etc.), so geothermal energy should be an example of where EROI analysis has been done thoroughly. However, our understanding of EGS EROI for power production has had substantial gaps and is frequently misunderstood. Clearly there is still work to be done to provide a through, up-to-date, defensible, peer reviewed EROI to guide EGS development and compare geothermal resources to other energy alternatives.

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Appendix: Preliminary Process Analysis of Wellfield Construction Energy

The first step in developing a Process Energy Analysis of the energy embodied in wellfield construction is to establish an inventory of the significant materials and then estimate the energy needed to "assemble" the materials. The materials with the most embodied energy, one would expect to be the casings, cement, pipelines, and downhole pumps. Other potentially important materials are the drilling mud, bits, and wellhead. The energy to "assemble" the materials includes that embodied in the drilling rig, the fuel to operate the rig, and the energy to construct the pipelines. This appendix is not a complete wellfield inventory of materials and embodied energy; it is a progress report of work so far.

To establish a baseline well, the work by ThermaSource for Sandia National Laboratories (Polsky, 2008 and Polsky, 2009) has been used. The key information in that work is the casing design and bit program (Figure A-1) which includes a complete casing specification including weight per foot by grade and lengths including overlap. Table A-1 shows the calculation of the total metric tons of steel needed to case this baseline 20,000 ft (6.1 km) well.

The ThermaSource's cement specifications included cement type, cement volumes (including excess, lead, and tail), and spacer volumes (Table A-2). For well designs that do not include specification of cement volumes, the annular volume can be calculated from the bit program and casing dimensions (fixed by

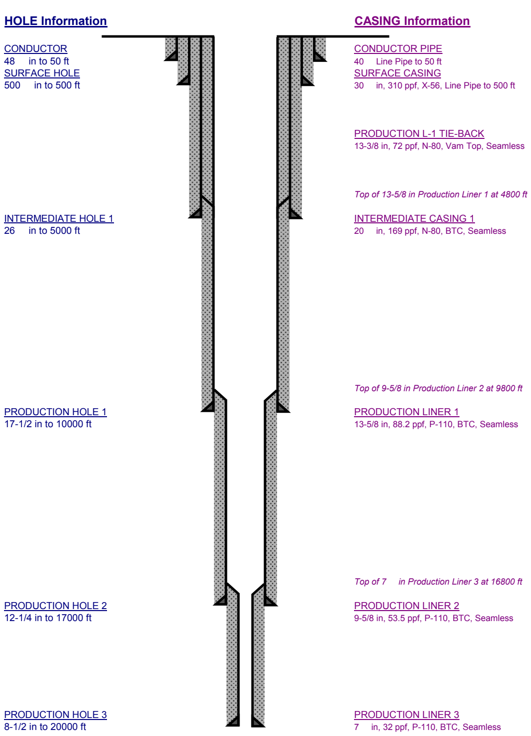

Figure A-1. Casing specification for base case well.

Table A-1. Calculation of metric tons of steel in casings.

Casing Schedule	Material	Length (ft)	(lb/ft)	Weight (Mg)
Conductor Pipe	Line pipe	50	428	10
Surface Casing	X-56, Line Pipe	500	310	70
Intermediate Casing	N-80, BTC, Seamless	5,000	169	383
Production Liner #1	P-110, BTC, Seamless	5,200	88.2	208
Production Liner #2	P-110, BTC, Seamless	7,200	53.5	175
Production Liner #3	P-110, BTC, Seamless	3,200	32	290
Production Tie-back Liner	N-80 Vam Top, Seamless	4,800	72	157
Total casing weight (Mg)				1,293

Table A-2. Cement specification and volumes.

Casing Schedule	Material	Cement (bbl)	Spacers (bbl)
Conductor Pipe	Class G	51	
Surface Casing	Class G	350	10
Intermediate Casing	Class G with 40% Silica Flour	2,030	120
Production Liner #1	Class G with 40% Silica Flour	940	120
Production Liner #2	Class G with 40% Silica Flour	605	70
Production Liner #3	Class G with 40% Silica Flour	115	45
Production Tie-back Liner	Class G with 40% Silica Flour	970	10
Totals		5,061	375

Table A-3. Cementing materials.

Cement volume (bbl)	Portland Cement (Mg)	Silica flour (Mg)	Water (gal)
5,061	772	275	135,370

Table A-4. Drilling fluid volume and composition.

Casing Schedule	Drilling fluid (bbl)	Water (gal)	Bentonite (ppb)	Soda Ash (ppb)	Gelex (ppb)	Polypac (ppb)	Xanthum Gum (ppb)	Polymeric Dis-persant (ppb)	High Temp Sta-bilizer (ppb)	Modified Lignite/ Resin (ppb)
Surface Casing	2,645	111,090	25	0.50	0.08					
Intermediate Casing	14,781	620,802	23	0.38		0.75	0.38			
Production Liner #1	7,440	312,480	18	0.25		0.75	0.38	0.04	0.04	0.08
Production Liner #2	5,104	214,368	14	0.25		1.00	0.50		1.5	3
Production Liner #3	1,053	44,226	11	0.25		1.5	0.75		3	1.5
Total (bbl)	31,023									
Total (gal)		1,302,966								
Total (Mg)			280	4.66	0.096	10.6	5.30	0.127	5.03	7.91

the casing grade and weight per foot) and multiplied by 150% to account for the excess cement required.[7] Based on the American Petroleum Institute specifications for Class G Cement (e.g. Halliburton's eRedbook), one can calculate the amounts of Portland cement, silica flour, and water required to cement the baseline well (Table A-3).

The drilling fluid recipes for the well was provided by ChemTech Services. Table A-4 summarizes materials (mid-range values of pounds per barrel - ppb) for each section of well. The ppb of materials for each drilling interval was selected by ChemTech Services to provide the required drilling fluid properties at temperature considering the length of time to drill each interval. Figure A-2 shows a surprisingly close correlation between the between the additional drilling fluid required for each interval and the volume of each interval. This correlation is essentially the same as that reported by EPA (1981). The value of this correlation is that, if the drilling fluid volume is not known, it can be estimated from the casing design and bit program of the well.[8]

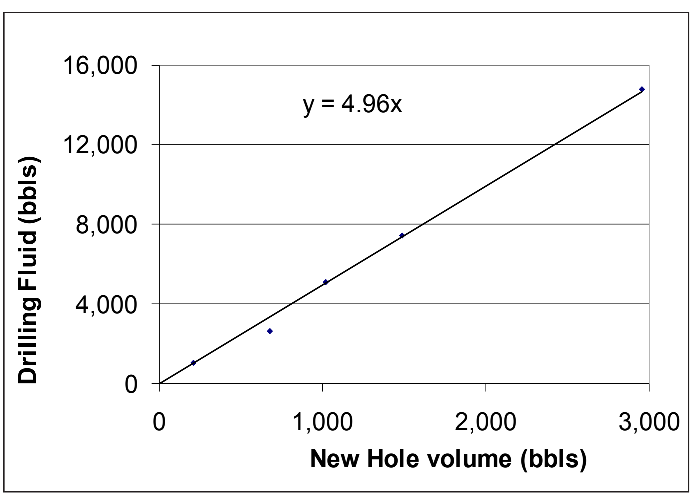

Figure A-2. Correlation between hole volume of each interval and additional drilling fluid.

Information on the materials for the production well electrical submersible pump (ESP) was provided by Hydro Resources. Materials for the ESP are divided into those dependent on the size of the pump and those that depend on the depth at which the pump is set. The former include motors, seals, pump, motor lead cable, and discharge assembly. For convenience these are labeled ESP-fixed. The latter category includes the power cable, banding, and column pipe. These are labeled ESP-per-foot. The quantity of materials in the ESP of course depends upon the flow rate and pressure head of the pump. These parameters need to be chosen trading off the productivity of the reservoir and power available from the power plant to run the pumps. As a preliminary estimate of the materials, a 950 gpm, 1,000 hp ESP set at 3,200 ft has been assumed. Table A-5 summarizes the ESP-fixed materials and Table A-6 summarizes the ESP-per-foot materials.

Table A-5. ESP-fixed materials.

Steel (Mg)	Copper (Mg)	Brass (Mg)	Lead (Mg)	Oil (Mg)	Rubber (Mg)
2.15	1.13	0.640	0.001	0.02	0.013

Table A-6. ESP-per foot materials.

	Steel	Copper	Rubber
lbs per foot	26.58	1.36	0.71
Total (Mg)	38.6	2.0	1.0

The materials needed for the wellfield pipeline include: steel (for pipeline, supports, and rebar), Portland cement, aggregate, forming tube (cardboard form for pouring the concrete), insulation (assumed for production wells, but not injection wells), water, and fuel. Based on preliminary work by Argonne National Laboratory for their Life Cycle Assessment (LCA) of geothermal power production, the materials per well for the pipeline are summarized in Table A-7. Assumptions are described in greater detail in two forthcoming reports (Clark et al., 2010 and Sullivan et al., 2010) and include 500 m of pipeline per well.

Table A-7. Wellfield pipeline materials.

Steel (Mg)	Portland Cement (Mg)	Card-board (Mg)	Insulation (Mg)	Water (gal)
52.3	52.8	3.40	3.45	6,171

Table A-8 summarizes the materials to construct a production well and calculates the embodied energy associated with each of these materials. Embodied energies per metric ton or gallon are taken from the GREET model (Burnham et al., 2006). Table A-8 includes the major contributions to the materials and energy needed to construct an EGS well and associated pipeline, but is

Table A-8. Summary of materials per well.

	Steel (Mg)	Portland (MG)	Silica Flour (Mg)	Copper (Mg)	Brass (Mg)	Lead (Mg)	Oil (gal)	Rubber (Mg)	Bentonite (Mg)	Soda Ash (Mg)	Organic Drilling Fluid Additives (Mg)	Modified Lignite/ Resin (Mg)	Cardboard (Mg)	Insulation (Mg)
Casing	1,293													
Cement		772	275											
Drilling fluid									280	4.66	21.1	7.91		
ESP	40.7			3.10	0.64	0.001	0.02	1.04						
Pipeline	52.3	52.8											3.40	3.45
Total	1,386	825	275	3.10	0.64	0.001	0.02	1.04	280	4.66	21.1	7.91	3.40	3.45
GJ/unit	28.5[10]	17.4[11]	0.116	30.6	84.4	29.2	45.5	43.9	1.40	12.9				
Energy (TJ)	39.5	14.43	0.032	0.01	0.05	<.001	<.001	0.05	0.39	0.06				

not complete. Items that have not yet been analyzed include: the wellhead, bits, hydrofracing, and the energy to pump the cement. The energy embodied in the other steel products such as the rig, drill pipe, drill collars used during well construction has been estimated to be about 1,300 Mg or on the order of that in the casing. However, when amortized over wells that can be drilled during the useful life of this equipment, this energy is less than 1% of the total energy input even before recycling of the steel is considered.

The baseline well was designed by ThermaSource assuming a location near Clear Lake, CA. Based on fuel consumption at actual wells drilled in that area and the use of a 3,000 hp rig with a top drive, ThermaSource assumed a fuel consumption rate of 2,500 gal per day.[9] The well construction plan for the baseline well was for 141 days resulting in a total fuel consumption of 352,500 gallons. Fuel for installing the pipeline is 9,975 gal per well (Clark et al., 2010). At an embodied energy of 0.16 GJ/gal (Brinkman et al., 2005), the energy associated with fuel use is 56.4 TJ for the drilling rig and 1.6 TJ for wellfield pipelines.

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[1] Sometimes referred to as emergy.

[2] Estimated from the gradient. The depths are not recorded in Herendeen and Plant 1979b. Depths have been revised from those reported in Mansure and Blankenship (2010).

[3] The energy to pump the cement has not yet been included.

[4] Clark, *et al*. 2010

[5] Herendeen and Plant in “Energy Analysis of Four Geothermal Technologies” (1979a) tabulate restimulation to be 3% of the input energy, but data tabulated in their report “Energy Analysis of Geothermal-Electric Systems” (1979b) places it at ~0.3%.

[6] The figure has higher EROI's than those presented at the Stanford Geothermal Workshop because depths have been recalculated and silica treatment costs have been removed.

[7] Application of this approach to this baseline well would have resulted in a 2.7% error in the total volume of cement needed.

[8] Estimating the total drilling fluid required for the baseline well from the casing design would result in a 1.6% error.

[9] That fuel consumption rate (0.833 gal per hp per day) is somewhat higher than the 0.65 gal per hp per day that has been used in WellCost Lite. For a description of WellCost Lite see Mansure et al. (2005).

[10] Burnham et al., 2006.

[11] Marceau et al., 2007.