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ARE GEOTHERMAL ENERGY RETURNS ON INVESTMENT HIGH ENOUGH?

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ABSTRACT

Energy Return On Investment (EROI) is an important figure of merit for assessing the viability of energy alternatives. If an energy technology has a low EROI, difficulties in defining the system boundaries and differences in quality of energy inputs and outputs become significant. There need to be compelling reasons for pursuing a technology with a low EROI. But what is a low EROI? An EROI of one is not adequate. To be useful to society, energy systems must generate more than just the energy required to be self-sustaining, they must support the balance of society. Published work on what is the "minimum" EROI energy systems need to have is discussed. One way of minimizing confusion regarding the effect of system boundaries and quality of energy on EROI is to close the loop, that is to use the system output energy as the investment energy for the next generation system. In the case of geothermal energy that means using electricity from one geothermal system to develop the next geothermal production system. The impact on geothermal EROI of closing the loop is examined. The benefit of using geothermal energy, as compared to fossil fuel, is examined for heating, electric power, and transportation based on past EROI analyses. This is done by comparing the merits of investing a barrel of fossil fuel directly in satisfying heating, electric power, and transportation demands vs. investing the barrel of fossil fuel in geothermal development and then using the geothermal energy for heating, electricity, and transportation.

INTRODUCTION

EROI is the ratio of the energy delivered to the energy consumed to construct, operate, and decommission the facility (Figure 1). Challenges in calculating EROI are system boundaries and the value of the energy inputs and outputs. One way the value of energy can formally be accounted for is using Gibbs 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. In this paper the issues of system boundaries and energy value is addressed by closing the loop – using geothermal produced energy to develop the next generation geothermal system.

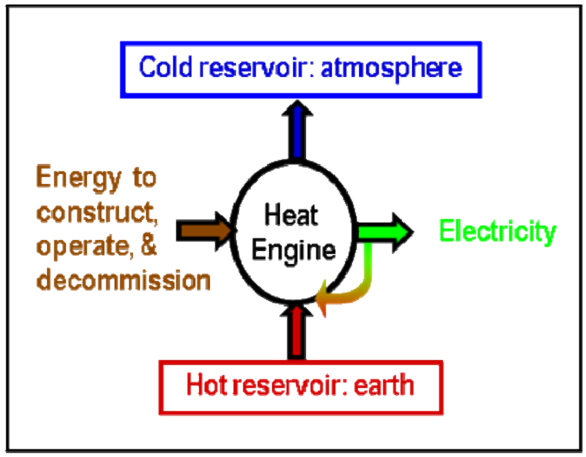

Figure 1: Geothermal heat engine converting energy, raw materials, and heat from the earth into electricity.

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. The methodology (Input/Output Analysis) and results of past geothermal EROI analyses have been reviewed as well as issues conducting and interpreting EROI analysis (Mansure and Blankenship, 2010 and Mansure 2010). The validity of past geothermal EROI estimates has been investigated by spot checking some of the major energy inputs into constructing geothermal wells using process analysis rather than economic data.

As the first step in a process analysis of an Engineered Geothermal System's (EGS) EROI, a material inventory has been developed for a baseline well (Mansure, 2010).[1] As US Department of Energy (DOE) sponsored Life Cycle Assessments (LCA) of alternative energies progress, the databases are changing that are used to calculate embedded or

[1] Materials that could contribute >1% to the wellfield construction energy.

burdened input energies from material quantities. Thus an updated material inventory and embedded energy table is provided as an appendix.

A consideration often overlooked in discussions of future renewable energy economies is the process of converting from fossil fuels to alternative energies. That issue is addressed in this paper by examining the benefits of investing fossil fuels in developing geothermal systems for heating, air conditioning, and transportation in addition to generating geothermal electric power.

AN EROI HIGH ENOUGH TO CONTRIBUTE TO THE BALANCE OF SOCIETY

For an energy source to be significant player in total energy consumption (visible on the pie chart), it should have an EROI high enough to have a significant net contribution to the balance of society rather than being a burden. Discussion of what is this "minimum" EROI has begun (Hall et al., 2009). The importance of EROI can be understood by considering the impact of changes in overall EROI on the Gross Domestic Product (GDP) that is EROI measured not at the energy extraction point, but at the consumer. Roughly 9%[2] of the US GDP in spent on energy. Discretionary spending is about 25% of the GDP (Hall et al., 2009). If the overall EROI were to double at no change in energy cost, approximately one third of discretionary spending would have to be reallocated. Thus, one measure of "are geothermal EROIs high enough?" is how will changing from fossil fuel to geothermal impact the overall EROI.

The focus of Hall et al.'s (2009) investigation of "minimum" or unsubsidized EROI is the use of petroleum to provide transportation. Petroleum is the US's largest source of primary energy supplying 37% of demand followed by natural gas, 25%, and coal, 21%.[3] The primary use of petroleum is for transportation, 72%, hence Hall et al.'s focus. Hall et al.'s approach was to start with the Exajoules of petroleum produced each year and calculate the energy costs to the consumer of providing transportation. They found production and refining to consume 20% of the petroleum produced, non-fuel refinery products 17%,[4] transporting fuel to the customer 3%, and transportation infrastructure (roads, bridges, etc.) 24%. Thus to deliver one barrel of fuel to the transportation customer, approximately three[5] barrels of petroleum must be produced. According to Hall et al. the "minimum" or unsubsidized EROI required by the customer is thus approximately 3 in the US.

Recognizing there are distinct differences between petroleum and geothermal energy (petroleum is both an energy source and raw material and has value as a highly portable liquid fuel) based on Hall et al.'s (2009) determination of "minimum" EROI, if geothermal power generation system has an EROI of 3[6] or more, it will integrate into the existing energy economy as an asset. As a point of comparison, in reference to corn-based ethanol Hall et al. say "an EROI of at least 3:1 is required for the fuel to not be subsidized by fossil fuels. EROIs above 3:1 are rarely reported for any liquid biofuels." Here Hall et al. are referring to the EROI at the farm gate. Thus they conclude corn-based ethanol farm gate EROI needs to double from the typically reported value of 1.3.

APPLYING GEOTHERMAL POWER TO TRANSPORTATION

It is not appropriate to calculate EROI without considering the values of input and output energies. As mentioned earlier the issues of value of the energy can be addressed using exergy or by closing the loop, but neither captures the full value of energy relative to transportation. Value metrics important to transportation include portability and storability. These are especially important considering the need for and difficulty in acquiring alternatives to fossil transportation fuels.

One way of assessing the applicability of geothermal power production to transportation is to compare the benefits of burning the barrel of oil as transportation fuel (using it in an internal combustion engine) vs. investing the barrel of oil in developing a geothermal power production system and using the electricity generated for transportation. This could be done by two alternative approaches: using geothermal electric power as an energy source for liquid fuel production or by using plug-in electric vehicles.

For the first approach one would still need the raw material for the fuel, carbon or in the case of hydrogen fuel, water. The energy needed to convert carbon compounds (biomass for example) into transportation fuel can in general most efficiently be accomplished using autothermal processes – processes where the heat is obtained by burning some

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[2] EIA (2009) http://www.eia.doe.gov/emeu/aer/txt/ptb0105.html.

[3] EIA (2009) http://www.eia.doe.gov/emeu/aer/pecss_diagram.html.

[4] Removing non-fuel refinery goods as a cost would reduce the "minimum" EROI value, but the consumer would have to pay the cost elsewhere. Thus they are the petroleum fuel sector's contribution to the balance of the economy.

[5] 1/(1-.2-.17-.03-.24)=2.8.

[6] An up-to-date EROI has yet to be calculated, but based on work done in the 1970's, 3 was a reasonable number to use (Mansure 2010).

of the raw material. To effectively meet the demand for energy, energy waste should be minimized which means high exergetic should not be converted to heat. Thus rather than converting geothermal power from electrons into carbon based chemical energy, a better way to use geothermal power for transportation would be to keep it as electrons and power electric vehicles. The question of using geothermal power to produce hydrogen fuel is different. The fuel would be produced from water by electrolysis which is not autothermal – one cannot burn water.

To compare burning a barrel of fuel in an internal combustion engine with investing it in geothermal energy to power an electric plug-in vehicle Saab's 9-3 Sports Combi will be used as a basis. This car is currently available as a diesel and it has been announced[7] that 70 plug-in electric 9-3 Sports Combis will begin customer trials in Sweden in 2011. Table 1 shows a comparison between diesel (1.9TTiD 180 hp Aut-6) and plug-in electric versions of this vehicle. Pictures of the 9-3 ePower Saab prototype show it to be the same body as the 9-3 Sports Combi diesel.

Table 1: Comparison of Saab 9-3 Sports Combi diesel and ePower prototype.

	ePower[7]	Diesel[8]	
engine	184	180	hp
acceleration	8.5	9.2	sec 100 km/h
top speed	150	215	km/h
energy storage	35.5	625[9]	kWh
km/kWh	5.6	1.4	
range	200	879	km
fuel cost $/km	0.026[10]	0.052[11]	

Table 1 shows the ePower Saab to have similar horsepower and acceleration as the diesel, but lower top speed. Presumably this is to optimize the use of the battery. The energy stored in the ePower battery is 6% of energy in the diesel fuel tank, but the km per kWh is more than four times that of the diesel resulting in a 200 km range for the ePower prototype or 23% of the diesel range. The batter pack is designed to charge overnight[12] and have a ten year life time. Thus while the storability of electric energy in the ePower prototype is enough to go three times the distance an average US car is driven in a day, it is not enough for road trips.

Based on an electricity cost of 10 ¢ per kWh[13] and a road tax of 0.78 ¢/km,[10] the energy cost per km for the ePower Saab is half the cost of diesel (Table 1). Thus cost is not a barrier to achieving the energy portability and storability necessary to use geothermal electric power for personal car transportation excluding road trips. On the other hand the difficulty in storing enough electrical energy for personal car use implies that geothermal power is not suitable for heavy truck and air transportation.

The customary performance metric for the effectiveness of converting liquid fuel into transportation is km per liter (mi/gal). For the diesel Saab 9-3 this is 15.2 km/l (35.6 mi/gal). If diesel[14] is burned in a existing[15] fossil fuel power plant with a nominal efficiency of 33%[16] and transmission line losses of 6.5%,[17] the effectiveness of the ePower Saab is 10.8 kWh/l * 33% * 5.6 km/kWh * 93.5% = 19 km/l (41 mi/gal). On the other hand if the diesel is invested in the development of a geothermal power plant with a nominal EROI of 3[6], the effectiveness becomes 10.8 kWh/l * 3 * 5.6 km/kWh * 93.5% = 170 km/l (400 mi/gal). Thus investing the diesel in geothermal is eleven times as effective as burning the diesel in an internal combustion engine. Similarly, the effectiveness of diesel used to produce hydrogen for a fuel cell vehicle can be calculated based on a 22% fossil fuel to wheel efficiency (Bossel, 2006). Table 2 provides a comparison of geothermal power's effectiveness in supporting personal vehicle transportation showing the effectiveness of investing energy in geothermal development.

Table 2: Effectiveness of geothermal power in personal vehicle transportation.

Diesel internal combustion	15 km/l	100%
Diesel burning power plant	19 km/l	115%
Diesel to Fuel cell	13 km/l	88%
Investment in geothermal	170 km/l	1120%

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7 Search for ePower on http://newsroom.saab.com.
8 http://www.saab.com/global/en/start#/Cars/9-3sport-combi/facts/equipment-levels/aer_otx/.
9 Based on 10.8 kWh/l diesel fuel, http://www.doi.gov/pam/eneratt2.html.
10 Based on 10 ¢ US per kWh for electricity plus 15% the price of diesel or 0.78 ¢/km for road tax.
11 Based on $3 US per gallon ($0.79/l).
12 "It can be fully recharged from a domestic mains supply in about three to six hours, depending on depletion status." According to Saab – footnote #7.
13 This paper is concerned with energy balances not costs. Thus it is assumed that geothermal power is competitive with other electrical power options.
14 Based on 10.8 kWh/l diesel fuel, http://www.doi.gov/pam/eneratt2.html.
15 The benefit of burning the diesel in a conventional plant needs to be reduced somewhat to account for the energy to construct the plant.
16 http://www.eia.gov/cneaf/electricity/page/co2_report/co2report.html.
17 http://tonto.eia.doe.gov/ask/electricity_faqs.asp#electric_rates2.

GEOTHERMAL HEATING AND COOLING

Should a barrel of fossil fuel be burned for heating or invested in extracting geothermal energy? Geothermal energy can be used for heating either by generating electricity or by direct heating. If geothermal energy is used to generate electricity which is then used in an electric heater, the benefit is the EROI for the geothermal power generation system which for this study is assumed to be 3[6] – that is 3 Joules of heat are delivered for each Joule of fossil fuel consumed. Note, burning diesel delivers ~0.87[18] Joules for each Joule consumed because of the efficiency of furnace heating systems, typically in the range of 78% to 95%

Significantly increased benefit can be obtained by using a geothermal heat pump. A geothermal heat pump with a Coefficient Of Performance (COP) of 3.6[19] using geothermal generated electricity would result in a 3 * 93.5%[17] * 3.6 = 10 fold return.[20] That is investing a Joule of fossil energy in geothermal electricity production to power a geothermal heat pump results in delivering 10 Joules of heat. The Joule of fossil fuel could be burnt in a thermal power plant and the resulting electricity used in a traditional heat pump, but in this case the Joule of fossil fuel would only produce 0.31 Joules of electricity after accounting for generation[21] and transmission losses. When used in an Energy Star rated traditional heat pump with a COP of 2.4,[22] return on the initial Joule of fossil energy would be 0.31 * 2.4 = 0.74 Joules or 7.4% that of geothermal.

A further benefit is the geothermal heat pump can be used for cooling. In this case the benefit or Joules of heat removed would be 48 Joules for each Joule of fossil fuel invested for a geothermal heat pump with an Energy Efficiency Ratio (EER) of 16.[19] For traditional power generation and heat pump the benefit is 0.31[21] * 12[22] = 3.72 Joules.

Since the energy required to construct a geothermal well increases non-linearly with depth,[23] it is "conservative" to investigate the benefits of geothermal district heating using a deep (6.1 km) EGS well.[24] Table 3 summarizes the parameters of a deep EGS well. The energy that can be delivered to the district heating system by a pair of these wells is 22 times the energy needed to construct the wells. The energy needed to construct an EGS well and the energy that can be produced are very dependent upon location. For example, if a 1.5 km well is drilled in the same local (same gradient as Table 3 resulting in a bottom hole temperature of 67°C), the energy that can be produced is reduced by 90%. However, the energy needed to construct the well is reduced by 88% so that the net benefit is almost the same (district heating EROI 21 instead of 22). On the other hand, if 100°C instead of 225°C was encountered at 1.5 km the district heating EROI would be 63. This supports the presumption above that it would be conservative to estimate the benefit of investing fossil energy in developing a geothermal district heating system using a deep EGS well.

Table 3: Deep EGS district heating well parameters.

Reservoir temperature	225 °C
Well depth	6.1 km
Reinjection temperature	50 °C
Flow rate	80 kg/sec[25]
Available enthalpy	758 kJ/kg
Capacity factor	25%[26]
Decline rate	6%[27]
Decline Cutoff[28]	50%
Well construction energy[29]	113 TJ

Table 4 summarizes the comparison between traditional heating and cooling vs. geothermal of the benefit that can be delivered starting with one Joule of fossil fuel. Where district heating demand is collocated with a geothermal resource, district

[18] American Council for an Energy-Efficient Economy http://www.aceee.org/consumer/heating#furnaces and Energy Star boiler rating http://www.energystar.gov/index.cfm?fuseaction=find_a_product.showProductGroup&pgw_code=BO.

[19] Direct Geoexchange (DGX), Energy Star tier 3 Geothermal Heat Pumps Key Product Criteria, http://www.energystar.gov/index.cfm?c=geo_heat.pr_crit_geo_heat_pumps.

[20] The energy to construct the heat pump needs to be added to the investment, but that energy has been estimated to be <<1% of the heat delivered by the heat pump and thus should be insignificant.

[21] http://www.eia.gov/cneaf/electricity/page/co2_report/co2report.html.

[22] http://www.energystar.gov/index.cfm?c=airsrc_heat.pr_crit_as_heat_pumps.

[23] This is a consequence of the increased number of casing strings and surface casing diameter, telescoping, required to construct deep wells.

[24] Well design by ThermaSource (Polsky, 2009).

[25] The high base case well flow rate in The Future of Geothermal Energy (MIT, 2006).

[26] US District Heating: Barriers and Enablers (Thorsteinsson, 2008).

[27] Twice that used in The Future of Geothermal Energy (MIT, 2006) to be conservative.

[28] An assumed number. Enthalpy production rate at which system is replaced.

[29] Note: this includes 3% for 1,000 m of surface piping and 1% for an Electrical Submersible Pump (ESP). For district heating systems with long delivery systems, the benefit may be reduced.

heating should give a higher EROI than geothermal power generation followed by geothermal heat pumps (22 vs. 10). Where they are not collocated, geothermal power generation followed by geothermal heat pumps is still over 10 times better than conventional options.

Table 4: Comparison of traditional heating and cooling vs. geothermal.

	Traditional	Geothermal	Ratio
Diesel furnace	0.86 J[18]	3 J	3.5
Electric heating	0.31 J[21]	3 J	10
Heat pump heating	0.74 J	10 J	14
Heat pump cooling	3.72 J	48 J	13
District heating	1.00 J[30]	22 J	22

CLOSING THE LOOP

The impact on EGS EROI of closing the loop, that is using geothermal power to develop the next generation energy, depends on the mix of material and energy inputs needed for EGS construction. Table 5 summarizes the energy inputs for the most significant materials as determined by LCA of EGS (Sullivan et al., 2010). Energy inputs can be a) chemical energy in the raw materials (e.g. energy released while producing coke from coal as part of steel production), b) consumption of fossil fuels (e.g. diesel fuel used by trucks hauling materials to the location), or c) electricity generated from primarily energy sources (Figure 2). Substitution of geothermal power for the raw material energy is impractical. Substitution of geothermal power for grid or on location generated power does not pose problems. Substitution of geothermal power for direct use of fossil fuel can be difficult as in the case of producing liquid fuel for use in trucks that haul materials to the location. Because of the high exergetic value of electricity, such problems are associated with the chemical processes, not the value of geothermal power. Thus, as shown in Figure 2 the most logical use of geothermal power (dotted line) would be to displace fossil fuels used to generate electricity (dashed line).

Baseline in Table 5 is the energy needed to construct 20 MW of EGS power production using DOE target (Augustine et al., 2010) well productivity and depletion. Savings is the reduction in input energy if geothermal power is substituted for fossil fuel generation of electricity. Net is input energy required closing the loop as shown in Figure 2.

Table 5 shows that closing the loop as shown in Figure 2 results in a 39% reduction in the energy needed to construct an EGS power generation system (31% for the power plant and 42% for the wellfield). Since the reduction is larger for the wellfield than the power plant, if the number of wells increases, the benefit of closing the loop increases, but not significantly. The data presented in Table 5 is for a 20 MW EGS plant; calculations for a 50 MW EGS plant are essentially identical.

Table 5: EGS primary material and energy inputs before and after switching to geothermal electric power.

Plant	Baseline	Savings	Net
Aluminum	165 TJ	26%[31]	123 TJ
Steel	111 TJ	39%[31]	68 TJ
Wellfield			
Diesel	223 TJ	63%[32]	82 TJ
Steel	493 TJ	39%[31]	301 TJ
Cement	124 TJ	17%[31]	103 TJ
Other	22 TJ	0%	22 TJ
Total	1,140 TJ		699 TJ

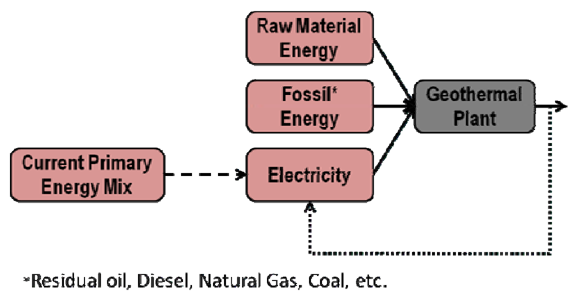

Figure 2: Substitution of current primary energy used to generate electricity with geothermal power.

In addition to reducing the energy to construct the system, to determine the impact of closing the loop on EROI one must account for closing the loop consumes some of the output energy. The change in EROI can be calculated as follows:

$$EROI_2 = \frac{EROI_1 - f}{(1 - f)} \qquad (1)$$

where $EROI_1$ and $EROI_2$ are the EROI before and after closing the loop and f is reduction in input energy, 0.39 for the case above. For an initial EROI of 3[6], the new EROI resulting from closing the loop as shown in Figure 2 is 4.3.

[30] The point of measurement is at consumption, thus distribution looses in delivering fossil fuels are not considered in any of these scenarios.

[31] As calculated by GREET by J.L. Sullivan (December 2010 energy burdens), personnel communication.

[32] Based on Caterpillar 1 MWe diesel generator set consuming 272 l/hr, http://www.cat.com/cda/files/847278/7/3512B1230ekwContLowEmission_SR5.pdf.

CONCLUSIONS

It takes energy to acquire more energy. Thus as new sources of energy are developed, it is important that they have a high EROI. High enough they don't require energy subsidies, high enough to decrease dependency on existing energy sources rather than accelerating depletion. Currently most countries depend upon fossil fuel, petroleum in particular, as their primary energy source. Thus the question how does a potential new source of energy compare with petroleum?

An EORI of 3 to the end use consumer has been proposed as the value a new energy system must achieve to substitute for petroleum without requiring a subsidy. Hall et al. (2009) calculated this value by considering the downstream consumption of petroleum products necessary to provide the infrastructure (roads, bridges, etc.) and fuel than runs the US transportation system. Similarly they calculated the increase in EROI of corn-base ethanol necessary to meet US ethanol consumption goals provided ethanol supported its share of the infrastructure. By coincidence this calculation also resulted in an EROI of 3.

An up-to-date EROI for geothermal power production has yet to be calculated, but based on work done in the 1970's (Herendeen and Plant, 1979 a&b), 3 was a reasonable number to use. Thus past work on geothermal EROI suggests geothermal energy development should integrate into the existing energy economy as an asset decreasing the depletion of fossil fuels.

Considering the need for and difficulty in acquiring alternatives to fossil transportation fuels, it is helpful to assess geothermal power's potential to contribute to transportation in terms of customary metrics of km/l (mpg). This is done by addressing the question what would be impact of investing diesel fuel in developing geothermal resources rather than using it as a transportation fuel. Geothermal can provide 11 times more km/l (mpg) than diesel fuel in a plug-in electric vehicle. Thus investing diesel in geothermal extends significantly the lifetime fossil fuels allowing fossil fuels be used where they are needed the most, heavy truck and air transport.

Considering portability and storability, geothermal gets a mixed review. Electrons are as portable as liquid fuel as measured by transport losses, but the storability of electric energy in batteries is significantly less than the storability of liquid fuel in tanks. This is in part mitigated by geothermal power providing base load minimizing the need for storage except in transportation vehicles.

Heating and cooling is another area where geothermal energy outperforms conventional options. Geothermal's heating performance ranges from 3.5 times more effective than fossil fuel furnaces to as much as 22 times or more for district heating systems. Geothermal heat pumps operating in cooling mode can be as much as 13 times more effective than conventional systems.

It is not practical to use geothermal generated power for all the input energy needed to constructing a geothermal power plant, but substituting it for the electrical input energy can increase the EROI by as much as 40% or more.

Thus in summary, geothermal systems can have high enough EROI's to integrate into the existing energy as a asset, requiring no energy subsidies, and thus reducing the rate fossil fuels are depleted. Furthermore, with the exception of limited storability of electricity in transportation vehicles, geothermal systems perform better than conventional systems in kilometers and heat delivered or removed per energy investment.

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APPENDIX: UPDATED BASELINE WELL MATERIAL INVENTORY AND EMBEDDED ENERGY

	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	25.1[33]	6.4[34]	0.116	30.6	84.4	29.2	45.5	43.9	1.40	12.9	90	1.8	17.8	2.7
Energy (TJ)	34.8	5.28	0.032	0.01	0.05	<.001	<.001	0.05	0.39	0.06	1.9	0.01	0.06	0.01

In addition to the 43 TJ in the above table, diesel fuel is required. Fuel estimates are as follows: rig 56.4 TJ, haulage 9.9 TJ, pipeline construction 1.6 TJ, and stimulation 2.0 TJ. Thus the total energy required to construct the baseline well designed by ThermaSource is 113 TJ.

[33] Burnham et al., 2006.
[34] Marceau et al., 2007.