ABSTRACT

Energy Return On Investment (EROI) is an important figure of merit for assessing the viability of energy alternatives. Too often energy systems are compared using "efficiency" when EROI would be more appropriate. For geothermal electric power generation, EROI is determined by the electricity delivered to the consumer compared to the energy consumed to construct, operate, and decommission the facility.

Critical factors in determining the EROI of Engineered Geothermal Systems (EGS) are examined in this work, specifically the energy embodied into the system. Embodied energy includes the energy contained in the materials, as well as, that consumed in each stage of manufacturing from mining the raw materials to assembling the finished system. Also critical are the system boundaries and value of the energy – heat is not as valuable as electrical energy.

The EROI of an EGS depends upon a number of factors that are currently unknown, for example what will be typical EGS well productivity, as well as, reservoir depth, temperature, and temperature decline rate. Thus the approach developed is to consider these factors as parameters. Since the energy needed to construct a geothermal well is a function of depth, results are provided as a function of depth. Parametric determination of EGS EROI is calculated using existing information on EGS and US Department of Energy (DOE) targets and is compared to the "minimum" EROI an energy production system should have to be an asset rather than a liability.

Introduction

EROI analysis is also referred to as Energy Return On Energy Investment, energy return, energy ratio, net energy, or energy payback ratio. A primary reason for conducting EROI analyses is to identify technologies that are potentially net energy sinks. Standard economic analyses do not necessarily distinguish between net energy producers and sinks especially when there are economic subsidies.

A geothermal power plant involves four energy streams: 1) heat extracted from the reservoir, 2) heat rejected to the atmosphere, 3) energy to construct, operate, and decommission the facility, and 4) electricity delivered to the customer. Heat extracted from the reservoir and heat rejected to the atmosphere are significant in determining the energy conversion efficiency of the system, but are not explicit factors in determining EROI. Efficiency is the ratio of the energy delivered to the customer to the energy extracted from the reservoir. Whereas, EROI is the ratio of the energy delivered to the customer to the energy consumed to construct, operate, and decommission the facility.

Past work (Mansure and Blankenship 2010, and Mansure 2010) reviewed methodologies for calculating EROI, as well as, calculations of geothermal EROI done in the 1970’s (Herendeen and Plant, 1979 a&b). Since the 1970’s there have been significant technological advancements that reduced the energy needed to construct geothermal wells. Also, presumptions made in the 1970’s regarding EGS reservoir sustainability have not been justified. Thus an up-to-date determination of EGS EROI is needed.

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. 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.

The energy to construct an EGS depends upon a number of variables, in particular, well depth and productivity. As the depth of a well increases, the energy needed to construct the well increases. If the power produced does not increase, then the energy cost increases with no increase in benefit resulting in an EROI that decreases with depth. There has been an increase in EGS well productivity since the 1970’s when EGS EROI estimates...
were based on work at Fenton Hill (Brown, 2009). However, there is still a gap between what has been demonstrated (Soultz for example, Genter et al. 2009) and DOE targets. There is no long term experience on which to base EGS temperature decline rates. (Temperature decline rate determines how often the wells must be replaced). Thus EGS EROI has been determined parametrically as a function of well depth and productivity, as well as, temperature decline rate.

A significant concern was “Is EGS EROI high enough to contribute to the balance of society?” This question was addressed by reviewing past work on the “minimum” EROI needed for a energy system to contribute to the balance of society and by comparing the benefit of investing fossil fuel in developing geothermal EGS vs. just consuming the fossil fuel (Mansure, 2011). For example, by comparing investing fossil fuel in developing geothermal power and using the geothermal power in a plug-in electric vehicle vs. burning the fossil fuel in an internal combustion vehicle. This work determined that, if geothermal systems have an EROI of 3 or more (actual “minimum” needed may be lower), the energy return would provide a sufficient contribution to the US energy economy to justify investing fossil fuel in developing geothermal systems. With this “minimum” EROI in hand, the parametric determination of EROI allows one to determine what well performances and reservoir temperature decline rates provide an adequate return on energy investment. Investing fossil fuels in developing EGS with more than the “minimum” EROI would reduce the rate fossil fuels are being depleted and reduce the rate CO₂ is released into the atmosphere.

The approach to determining EROI presented in this paper is based on process engineering, summing up the energy needed in each step from mining the raw materials to assembling the final product. Two primary sources for the information have been used: the DOE sponsored Life Cycle Assessment (LCA) of geothermal energy (Sullivan et al., 2010) and detailed material inventories of well construction developed for this project (updated from Mansure, 2010). The primary additional information needed is the diesel fuel consumed. Fuel is consumed to construct and stimulate the wells and transport the materials to the site. The embodied energies used are those incorporated into the GREET model (Burnham et al., 2006).

Methodology

Energy must be invested to develop an EGS both in the power plant and wellfield. EROI of an EGS power production system is determined by the following formula:

\[
\text{EROI} = \frac{E_{\text{grid}}}{E_{pp} + E_w (\eta_i + 1)(1 + r)(1 + n_r)},
\]

where \(E_{grid}\) is the net energy sold to the grid over the life of the project and is determined using GETEM (Mines, 2008). The net energy sold to the grid is calculated using baseline data from the EGS LCA (Sullivan et al., 2010) and DOE targets (Augustine et al., 2010). Discussion of the use of GETEM can be found in the project final report (Mansure, 2012). \(E_{pp}\) is the embodied energy needed to construct the power plant. From the EGS LCA the embodied energy needed to construct the power plant is 815 TJ for a 50 MW power plant. \(E_w\) is the embodied energy needed to construct a well. The approach to calculating the embodied energy needed to construct a well was previously presented to the Geothermal Resources Council (Mansure, 2010) and is updated in the project final report. \(n_i\) is the initial number of EGS flow loops as determined by GETEM. The +1 following the initial number of EGS flow loops provides a spare flow loop to maintain system output during wellfield maintenance and outages. \(r\) is the ratio of injectors to producers within a flow loop. The ratio of injectors to producers is determined by the strategy employed to develop the flow loops. \(n_r\) is the number of times the flow loops have to be replaced as determined by GETEM. While the net energy sold to the grid and the initial number of EGS flow loops are potentially dependent upon a large number factors, the significant ones for an EGS are reservoir temperature, production well flow rate, and reservoir temperature decline rate.

Local geology affects the design of a geothermal well and hence the embodied energy. However, the affects of well design are much less significant than the change in embodied energy due to well depth. The embodied energy to construct an EGS well as a function of well depth can be calculated using the following equation (Mansure, 2012):

\[
E_w = (1.0625z^2 + 8.9285z + 12.8)TJ,
\]

where \(z\) is the well depth in km.

Combining equations 1 & 2:

\[
\text{EROI} = \frac{E_{\text{grid}}}{815TJ + (1.063z^2 + 8.93z + 12.8)(n_i + 1)(1 + r)(1 + n_r)TJ}.
\]

Results

EGS EROI ranges from very high to marginal depending upon the properties of the reservoir being developed (Figure 1).

![Figure 1. EROI or number of wells as a function of depth, temperature, and production well flow rate. Top set of curves is for 2,000 m, middle 6,000 m, and bottom 10,000 m deep wells. The dark horizontal line at EROI = 3 is the “minimum” EROI needed to be an energy asset rather than liability according to Hall and Murphy (2009).](image-url)
Parameters fixed for Figure 1 are annual temperature decline rate at 0.5% and injector to producer ratio at 1. The figure shows EROI’s from a low of less than 3 to over 30. That is a tenfold variation from less than the “minimum” needed EROI to be an energy asset according to Hall and Murphy (2009) (see subsequent section for discussion of “minimum” EROI) to an EROI greater than published average numbers for oil and gas energy resources (Cleveland, 2005). The three sets of curves on Figure 1 are for the depths 2,000 m, 6,000 m, and 10,000 m. Each set of curves contains data for resource temperatures from 225°C to 150°C and production well flow rates from 90 kg/sec to 30 kg/sec. Data for a given temperature but varying flow rates are connected and labeled by color. Overall the Figure 1 shows that EROI is very dependent upon the number and depth of the wells.

On Figure 1 the highest set of curves with EROI’s ranging from over 30 to about 12 is for 2000 m deep wells. 2,000 m would be a very shallow EGS, one for which reservoir temperatures would not normally be high. So perhaps at this depth a more reasonable range of EROI’s would be those for 150°C or an EROI from just over 20 to about 12. Similarly, one would not drill an extra deep or 10,000 m well unless there was an expectation of high reservoir temperatures and so EROI’s below 5 are not as likely as those over 5. EROI’s for the 6,000 m curve set, a reasonable depth target for EGS, range from 19 to 5. Thus considering likely reservoir depths, temperatures, and production well flow rates, a reasonable range of EGS EROI’s is 5 to 20 presuming a 0.5% temperature decline rate and an injector to producer ratio of 1.

Figure 1 includes data showing the affects of reservoir temperature, production well flow rate, and depth, but not all the potentially significant parameters. Figure 2 shows the relative importance of depth, production well flow rate, temperature, injection to producer ratio, and temperature decline rate. The baseline data for this sensitivity plot is given in Table 1. This baseline has an EROI of 14 conveniently near the middle of the range noted above. The end points of the input parameters (horizontal axis on Figure 2) for reservoir temperature, production well flow rate, depth, and ratio of injectors to producers were chosen to be reasonable bounds on these parameters. The figure shows that ratio of injectors to producers is not as significant as the parameters included in Figure 1 (depth, flow rate, and temperature). On the other hand, Figure 2 shows that temperature decline rate is potentially the most significant factor.

The EROI vs. temperature decline rate shows a sudden downward jump when temperature decline rate increases to more than 100% of the baseline (Figure 2). That is because at about a temperature decline rate 0.63% the power sales to the grid have declined sufficiently that a replacement set of flow loops is needed. The DOE goal is to develop techniques to engineer EGS reservoirs such that the flow loops do not have to be replaced (Augustine et al., 2010). With that goal in mind Sullivan et al. (2010) used a temperature decline rate of 0.5%. In contrast, the Future of Geothermal study (Tester et al., 2006) assumed a thermal decline rate of 3%. Figure 3 shows the affect of temperature decline rate on EROI for several reservoir temperatures and flow rates. Fixed parameters in Figure 3 are the depth at 6,000 m and injector to producer ratio of 1. The figure shows that the temperature decline rate at which flow loops must be replaced for the first time is not greatly affected by other parameters and that the choice of 0.5% as the temperature decline rate for DOE’s target of not having to replace flow loops was reasonable. Figure 3 further shows that for reasonable temperatures and flow rates (> 175°C & 60 kg/sec) the “minimum” EROI needed to be an energy asset (according to Hall and Murphy, 2009) is achievable even if the flow loops have to be replaced twice.

Table 1. Baseline data for sensitivity study.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resource Temperature</td>
<td>190 °C</td>
</tr>
<tr>
<td>Resource Depth</td>
<td>6000 m</td>
</tr>
<tr>
<td>Ratio of Injectors to Producers</td>
<td>1 N/A</td>
</tr>
<tr>
<td>Production Well Flow Rate</td>
<td>60 kg/s</td>
</tr>
<tr>
<td>Annual Rate of Temperature Decline</td>
<td>0.32 % of Initial Temperature</td>
</tr>
</tbody>
</table>

Figure 2. Sensitivity EROI to parameter changes.

Figure 3. EROI as a function of temperature decline rate and various temperatures and flow rates. Vertical dashed line is temperature decline rate used in The Future of Geothermal.

Figure 3 provides insight into the impact of reservoir decline rate at 6000 m. However, as depth changes EROI changes. Figure 4 shows EROI as a function of temperature decline rate for a
An EROI High Enough to Contribute to the Balance of Society

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.

Hall and Murphy (2009) have initiated the discussion of what is this “minimum” EROI an energy system needs to be an asset rather than a liability. The importance of EROI, according to Hall and Murphy’s arguments, 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 8% of the US GDP is spent on energy. According to Hall and Murphy discretionary spending is about 25% of the GDP. If switching from cheap, high EROI fossil fuels to more expensive, lower EROI alternatives were to require a doubling of upstream energy extraction to deliver the same energy to the consumer, a significant portion 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 energy impact the overall EROI.

Hall and Murphy’s (2009) argument for the “minimum” needed EROI is roughly as follows: petroleum is the largest source of primary energy in the US and most of that petroleum is used for transportation. Hall and Murphy’s analysis concluded that 3 barrels of petroleum must be extracted to deliver a barrel of service to the end use transportation customer after considering petroleum consumed in production, refining, delivery to the consumer, and transportation infrastructure (roads, bridges, etc.). Thus they concluded that the “minimum” EROI an alternative fuel must have to displace fossil fuels as an energy asset, not energy liability, is 3.5.

Applying Geothermal Power to Transportation

One way of assessing the applicability of geothermal power production to transportation is to compare the benefits of burning a barrel of oil as transportation fuel (using it in an internal combustion engine) vs. investing the barrel of oil in developing geothermal power production and using the electricity generated for transportation. The best approach to do this is to use plug-in electric vehicles rather than geothermal power as an energy source for liquid fuel production (Mansure, 2011).

To compare burning a barrel of fuel in an internal combustion engine with investing it in geothermal energy for an electric plug-in vehicle, Saab’s 9-3 Sports Combi was used as a basis (Mansure, 2011). This car is currently available with a diesel internal combustion engine and plug-in electric (ePower) prototypes have been displayed at auto shows. 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 version range. The battery pack is designed to charge overnight and to 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.

The customary performance metric for the effectiveness of converting liquid fuel into transportation is km per liter (mi/gal). Table 2 compares the effectiveness of various ways using diesel for personal vehicle transportation including internal combustion engines, generating hydrogen for use in fuel cell vehicles, plug-in electric vehicles powered by a central power plant burning diesel, and investing in developing geothermal power for plug-in electric vehicles. Investment in geothermal approach is based on a “minimum” EROI of 3 and a mid-range value of 13. Details of the calculations can be found in Mansure (2011).

<table>
<thead>
<tr>
<th>Ways of Using Diesel</th>
<th>Km/l</th>
<th>% Current Usage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Internal combustion engine</td>
<td>15</td>
<td>100%</td>
</tr>
<tr>
<td>Diesel synthesis of hydrogen for fuel cell vehicle</td>
<td>13</td>
<td>90%</td>
</tr>
<tr>
<td>Plug-in electric vehicle powered by central power plant</td>
<td>19</td>
<td>120%</td>
</tr>
<tr>
<td>Powering a plug-in electric vehicle by investment in geothermal @ an EROI of 3</td>
<td>170</td>
<td>1,120%</td>
</tr>
<tr>
<td>Powering a plug-in electric vehicle by investment in geothermal @ an EROI of 13</td>
<td>737</td>
<td>4,850%</td>
</tr>
</tbody>
</table>
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 generated electricity is used in an electric heater, the benefit is the EROI of the geothermal power generation system which for this study is assumed to be at least 3 or a mid-range value of 13 — that is more than 3 to 13 Joules of heat are delivered for each Joule of fossil fuel consumed. Note, direct burning of diesel delivers –0.87 Joules for each Joule consumed because of the efficiency of furnace heating systems, typically in the range of 78% to 95%.

A 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\(^8\) using geothermal generated electricity would result in greater than a 10 fold return (EROI\(_{EGS} \times 93\% \times 3.6\)). That is investing a Joule of fossil energy in geothermal electricity production to power a geothermal heat pump results in delivering more than 10 Joules of heat. The Joule of fossil fuel could be burnt in a thermal power plant and the resulting electricity used in an electric heater, but in this case the Joule of fossil fuel would only produce 0.31 Joules of electricity after accounting for generation and transmission losses. When used in an Energy Star rated traditional heat pump with a COP of 2.4, return on the initial Joule of fossil energy would be 0.31 \times 2.4 = 0.74 Joules or less than 8% that of geothermal.

A geothermal heat pump can be used for cooling. In this case the benefit for a geothermal heat pump with an Energy Efficiency Ratio (btu/kWh) of 16 would be EROI\(_{EGS} \times 93\% \times 16 \times 0.29 \geq 13 \) Joules for each Joule of fossil fuel invested. For traditional power generation and heat pump the benefit is 0.31 \times 12 \times 0.29 = 1.1 Joules or less than 9% that of geothermal.\(^{10}\)

Since the energy required to construct a geothermal well increases non-linearly with depth, it is “conservative” to investigate the benefits of geothermal district heating using a deep (6.1 km) EGS well. Mansure (2011) estimated 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 based on a bottomhole temperature of 225°C.

Table 3 summarizes the comparison of the benefit that can be delivered starting with one Joule of diesel fuel between traditional heating and cooling vs. geothermal.

<table>
<thead>
<tr>
<th></th>
<th>Traditional</th>
<th>Geothermal @ EROI 3</th>
<th>Geothermal @ EROI 13</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diesel furnace</td>
<td>0.87 J</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Electric heating</td>
<td>0.31 J</td>
<td>3 J</td>
<td>13 J</td>
</tr>
<tr>
<td>Heat pump heating</td>
<td>0.74 J</td>
<td>10 J</td>
<td>44</td>
</tr>
<tr>
<td>Heat pump cooling</td>
<td>1.1 J</td>
<td>13 J</td>
<td>56</td>
</tr>
</tbody>
</table>

Closing the Loop

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 benefit on EGS EROI of closing the loop depends on the mix of material and energy inputs needed for EGS construction. 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. Substitution of geothermal power for the raw material chemical energy is impractical considering the need for the material itself. Substitution of geothermal power for transportation 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, the difficulty is associated with the chemical processes, not the value of geothermal power. Fortunately transportation energy is on the order of only 10% of the EGS construction energy. Substitution of geothermal power for grid or on location generated electric power does not pose problems. Thus the most logical use of geothermal power to close the loop would be to displace fossil fuels used to generate electricity.

Based on the energy needed to develop a 20 MW of EGS power using DOE targets (Augustine et al., 2010), closing the loop through using geothermal generated power (inputs “c” in paragraph above) would result in a 39% reduction in the EGS construction energy (Mansure, 2011). 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:

\[
EROI_{\text{c}} = \frac{EROI_{1} - f}{1 - f},
\]

where EROI\(_1\) and EROI\(_c\) 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, the new EROI resulting from closing the loop is 4.3. For an initial EROI of 13 (middle of the range of EROI’s determined above), the new EROI resulting from closing the loop is 20. This suggests the impact of closing the increases geothermal EROI’s; however, the potential impact of synthesizing transportation fuel has not been considered.

Future Technology Impacts

Past geothermal technology advances have increased geothermal EROI’s since the 1970’s raising the question of the potential for future technology impacts. By far the largest contribution to the embodied energy needed to construct an EGS is in the fuel and materials needed to construct the wells. The fuel consumed can be reduced by more efficient drilling. To reduce the materials significantly, the design of the wells must change to reduce the steel and cement needed. A recent test by Sandia National Laboratories has demonstrated the potential for improving geothermal drilling rates of penetration (ROP) by using polycrystalline diamond bits (PDC’s) (Raymond, 2012). Increasing ROP reduces the days required to drill a well and hence the fuel consumed. Monobore well designs using expandable tubulars have been under develop-
ment in the oil and gas industry (Simonds and Swan, 2000). In theory this technology could significantly reduce the steel and cement needed to case an EGS well.

For the 10 km well analyzed as part of this project, these technology improvements could, in theory, reduce the embodied energy up to 50% essentially doubling the EROI. Reducing the embodied energy of deep EGS wells would have two significant impacts. It could allow EGS wells to be drilled deeper without the EROI dropping below the “minimum” EROI of 3. Also it would allow higher temperature decline rates without the EROI dropping below the “minimum” EROI of 3.

Conclusion

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 that they don’t require energy subsidies, high enough to decrease dependency on existing energy sources rather than accelerating their depletion. Currently most countries depend upon fossil fuel, petroleum in particular, as their primary energy source. Thus the question, how does a potentially new source of energy compare with petroleum? An EROI 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 an energy subsidy. Hall and Murphy (2009) proposed this “minimum” needed EROI value by considering the downstream consumption of petroleum products necessary to provide the infrastructure (refining, distribution, roads, bridges, etc.) and fuel than runs the US transportation system.

While a wide range of EGS EROI’s are possible, it is anticipated for EGS reservoirs with reasonable characteristics (depth, temperature, flow rate, and temperature decline rate) EROI’s will be achieved significantly above the “minimum” EROI required for EGS to contribute to the energy economy as an asset slowing the depletion of fossil fuels. Of these characteristics temperature decline rate is most challenging both in establishing bounds and analyzing the impact. Cost of EGS is outside the scope if this work, however, because of the correlation between costs, material consumption, and embodied energy, it is anticipated that cost competitive EGS would have high EROIs.

Closing Remark

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 while the system boundaries used in this study do not encompass every impact of developing and decommissioning an EGS system, they do not omit significant impacts and should be sufficient to calculate EROI values that are as complete as other energy alternatives. That is a result of the nature of a geothermal system – a simple heat engine.

Acknowledgements

The assistance of TheraSource and ChemTech Services in developing the material inventory used for the baseline well and the assistance of Randy Badger of Hydro Resources in supplying information on electrical submersible pumps (ESP) are gratefully acknowledged. Argonne National Laboratory’s assistance in providing reference values for the energy embodied into manufactured materials has been invaluable. Access to Sandia National Laboratories’ well drilling data is gratefully acknowledged. Both Argonne National Laboratory and Sandia National Laboratory have provided guidance for this work. This work was performed under contract to the US Department of Energy, Geothermal Programs Office, grant DE-EE0002740.

References


1 EGS can stand for either Enhanced Geothermal System or Engineered Geothermal System. An Engineered Geothermal System is one where the reservoir is created as a set of discrete flow loops connecting injectors and producers. The energy to construct discrete flow loops will normally be higher than the energy to enhance an existing geothermal reservoir. Thus, the subject of this project is Engineered Geothermal Systems.

2 Elsewhere in this study a temperature decline rate of 0.5% has been used for consistency with other DOE sponsored work, in particular, Argonne National Laboratory’s LCA (Sullivan et al., 2010).

3 In fact the sensitivity study baseline temperature decline rate of 0.32% was chosen to be half way to this jump at 0.63%.

4 The actual “minimum” EROI may be less and there has been some degree of conservatism (underestimating EGS actual EROI) built into this analysis to compensate for minor embodied energies needed to construct, operate, and decommission the facility that have not been explicitly accounted for in this analysis.

5 More discussion of Hall and Murphy’s work can be found in Mansure (2011); however, it should be noted that the statement there “If the overall EROI were to double at no change in energy cost, approximately one third of discretionary spending would have to be reallocated.” should read “If twice the energy were needed at the extraction point to deliver the same energy to the customer, approximately one third or more of discretionary spending would have to be reallocated.”

6 With Saab’s bankruptcy, development of the ePower 9-3 Sports Combi beyond prototypes maybe questionable. However, the numbers presented here are supported by specifications for the Tesla model S which has the same efficiency (km/kWh) but even longer range (http://www.teslamotors.com/models/features/#/battery).

7 Based on analysis by Bossel (2006).

8 Energy Star ratings have been used for heat pumps.

9 According to EIA data electricity transmission losses are ~7%; http://www.eia.gov/tools/faqs/.

10 Numbers in previous paper (Mansure 2011) had a unit conversion error.