NATIONAL ENERGY TECHNOLOGY LABORATORY

Role of Alternative Energy Sources: Geothermal Technology Assessment

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Acronyms and Abbreviations

ASTM	American Society for Testing and Materials
BLM	Bureau of Land Management
C	Celsius
CH_4	Methane
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
COE	Cost of electricity
DOE	Department of Energy
EERE	Energy Efficiency and Renewable Energy
EGS	Enhanced geothermal systems
EJ	exajoule
EIA	Energy Information Administration
EIS	Environmental impact statement
EPA	Environmental Protection Agency
ft.	foot
GHG	Greenhouse gas
GW	Gigawatt
GWP	Global warming potential
IPCC	Intergovernmental Panel on Climate Change
INL	Idaho National Laboratory
IRROE	Internal rate of return on equity
ISO	International Organization for Standardization
J	joule
km	kilometer
kW	kilowatt
lbs.	pounds
LC	Life cycle
LCA	Life cycle analysis
LCC	Life cycle cost
LCOE	Levelized cost of electricity
m	meter
m^2	square meter
MACRS	Modified accelerated cost recovery system
mi.	mile
MIT	Massachusetts Institute of Technology
MW	Megawatt
MWh	Megawatt-hour
N/A	Not applicable
N_2O	Nitrous oxide
NETL	National Energy Technology Laboratory
NGCC	Natural gas combined cycle
NO_X	Nitrogen Oxides
NREL	National Renewable Energy Laboratory
O&M	Operating and maintenance
PSFM	Power Systems Financial Model
RFS2	Renewable Fuel Standards 2
RMA	Raw material acquisition
RMT	Raw material transport
SF_6	Sulfur hexafluoride
SO_2	Sulfur dioxide
T&D	Transmission and distribution
TWh	Terawatt-hour
USDA	United States Department of Agriculture
USGS	United States Geological Survey

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Executive Summary

This report discusses the role of geothermal power in meeting the energy needs of the U.S. This includes an analysis of key issues related to geothermal power and, where applicable, the modeling of the environmental and cost aspects of geothermal power.

The U.S. has a large resource base of geothermal energy, but there are barriers to developing this resource. Assuming that sufficient technologies were to become available to support geothermal resource extraction, the total resource base within the U.S. is enormous. Development of only one percent of this resource would be equivalent to over 1,000 times the annual consumption of primary energy in the U.S. (INL, 2006). However, the harnessing of a geothermal resource is constrained by several factors, including the character of geologic formations (which can affect cost and feasibility of drilling), temperature and depth of the resource, and the proximity of the resource to available infrastructure (including power lines and supply/access roads). These factors pose significant limitations with respect to the ongoing development of domestic geothermal resources.

Geothermal power has not exhibited significant growth within the last decade. The fraction of total U.S. power generation from geothermal power has remained essentially constant since 2000, fluctuating from approximately 0.36 to 0.38 percent, representing a very small portion of total domestic power generation capacity. Recent trends indicate resurging interest in geothermal energy; as reported by the Geothermal Energy Association (GEA) the installation of new and expanded geothermal capacity increased from 2007 through 2009, with new projects and expansions increasing from 34 MW in 2006, to 176 MW in 2009 (GEA, 2011). The recent expansions reported by GEA are reflected by Energy Information Administration (EIA) statistics, which show a net change of 178 MW of geothermal power in 2009 (EIA, 2011b)[1].

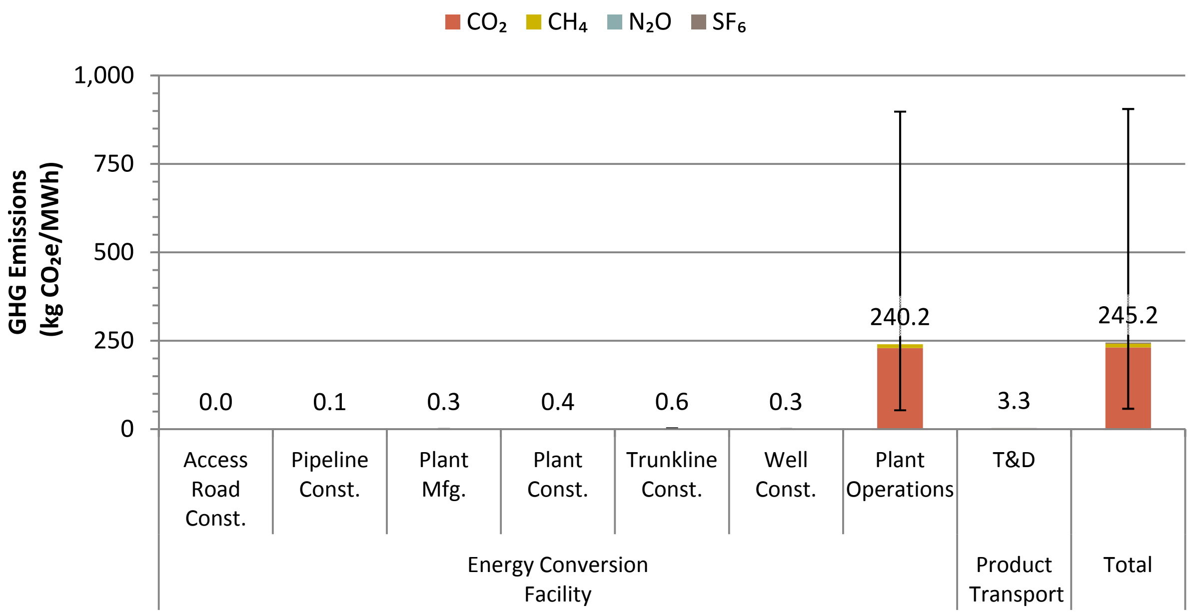
The geothermal power plant modeled in this analysis has a net capacity of 50 MW and is representative of the flash steam geothermal technology. A 50 MW flash steam geothermal power plant consists of 25 production wells, each having a depth of up to two miles. The production wells contain hot water at high pressure; when the water is brought to the surface, it is expanded in a flash vessel to produce steam that is used to drive a steam turbine. Steam condensate from the flash process is used to provide makeup water to the power plant's cooling water system, and thus it is not necessary to withdraw cooling water from other sources. All water that is recovered from the system is returned to the ground using injection wells. A 50 MW geothermal power plant has approximately 10 injection wells.

The boundaries of the life cycle analysis (LCA) account for the cradle-to-grave energy and material flows for geothermal power. The key environmental metrics that are accounted for in this analysis are greenhouse gas (GHG) emissions from the life cycle (LC) of geothermal power, including GHG emissions from land use change, as well as other air emissions, water use, and resource energy. The boundaries include five LC stages, beginning with raw material extraction; including the intermediate steps of raw material transport, energy conversion, and electricity transmission and distribution; and ending with electricity delivered to the consumer. In contrast to fossil energy and some forms of renewable energy conversion, geothermal power does not incur any environmental burdens for the

[1] Earlier versions of EIA's Electric Power Annual do not include a category for geothermal power additions, so no data are available to verify GEA's reported values for new geothermal power in 2006.

acquisition and transport of primary fuel because the installation and operation of wells are accounted for as part of the energy conversion facility (LC Stage #3). Thus, the equipment manufacture and construction and installation requirements of geothermal power plants dominate the LCA results for geothermal power as shown in **Figure ES-1**.

Figure ES-1: Life Cycle GHG Profile for Flash Steam Geothermal Power



The LC GHG emissions for the geothermal power system in this analysis are 245 kg of carbon dioxide equivalents (CO_2e) per MWh. The GHG profile for geothermal power is dominated by carbon dioxide (CO_2). The main source of these CO_2 emissions is noncondensible gases released by the flash steam geothermal power plant. Water from geological formations (called "geofluid") has naturally-occurring CO_2 and other gases that are released by the flash steam process. The CO_2 emitted by the flash steam geothermal power plant accounts for 93.6 percent of total LC GHG emissions. The expected GHG emissions are 245 kg CO_2e/MWh, but when the uncertainty of all parameters is combined, the GHG emissions range from 57.8 to 906 kg CO_2e/MWh. This wide range of uncertainty is mostly driven by variability in portion of noncondensible gas in the geofluid. This analysis accounts for uncertainties in other parameters, such as plant life, number of wells per unit of power plant capacity, length of access roads, and well depth; the GHG results of the analysis are more sensitive to changes in geofluid composition than other parameters.

The results discussed above do not account for the GHG emissions from land use change. The GHG emissions from direct and indirect land use change are an additional 2.0 kg CO_2e/MWh. The land use GHG emissions from geothermal power increase the total LC GHG emissions from 245 to 247 kg CO_2e/MWh, a 0.8 percent increase.

The life cycle costs (LCC) of geothermal power were calculated by performing a discounted cash flow analysis over the lifetimes of a geothermal power plant. The LCC analysis accounts for the significant capital and operating and maintenance (O&M) costs incurred by the system. The expected capital costs for a geothermal power plant are $3,000/kW. The fixed O&M costs for geothermal power are $164,600/MW-year (Tidball, Bluestein, Rodrigues, & Knoke, 2010)

The LCC model calculates the cost of electricity (COE), which is the revenue received by the generator per net MWh during the first year of operation (NETL, 2010b). The expected COE for geothermal power is $77.19/MWh. This result is representative of a low-risk investor-owned utility with a 50/50 debt to equity ratio, a 4.5 percent interest rate, and an internal rate of return on equity of 12 percent. The results for COE account for the seven percent loss during transmission and distribution and are expressed in 2007 constant dollars.

The risks of implementing geothermal power include public objections based on the potential interference with aesthetic resources and water resources. Aesthetic issues are a matter of perception and are difficult to address. Long-term degradation of groundwater quality due to geothermal power production has not been widely documented. However, short-term water degradation may occur during the construction process. There is also a growing public awareness regarding potential for induction of seismic activity due to geothermal power production.

Geothermal industry representatives are expressing positive forecasts for geothermal power. This surge in optimism comes after decades of sluggish interest in geothermal energy, and has been driven by recent pilot scale applications of new technologies, as well as discovery of new potentially exploitable resources.

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1 Introduction

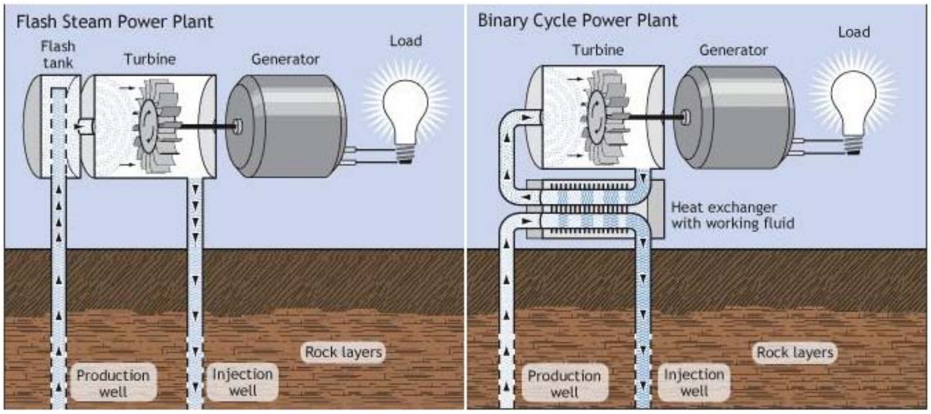
The role of an energy source in the national energy supply is determined by a combination of factors, including technical considerations, resource availability, environmental characteristics, economics, and other issues that may pose risks or barriers. The objective of this analysis is to conduct a broad assessment of geothermal power using a list of seven criteria as summarized in **Table 1-1**.

Table 1-1: Criteria for Evaluating Roles of Energy Sources

Criteria	Description
Resource Base	Availability and accessibility of natural resources for the production of energy feedstocks
Growth	Current market direction of the energy system – this could mean emerging, mature, increasing, or declining growth scenarios
Environmental Profile	Life cycle (LC) resource consumption (including raw material and water), emissions to air and water, solid waste burdens, and land use
Cost Profile	Capital costs of new infrastructure and equipment, operating and maintenance (O&M) costs, and cost of electricity (COE)
Barriers	Technical barriers that could prevent the successful implementation of a technology
Risks of Implementation	Non-technical barriers such as financial, environmental, regulatory, and/or public perception concerns that are obstacles to implementation
Expert Opinion	Opinions of stakeholders in industry, academia, and government

Geothermal energy is accessed by drilling wells a mile or deeper below the surface of the Earth. There are several technologies for converting geothermal energy to electricity, but the two most common technologies in the U.S. are flash steam and binary technologies. Flash steam geothermal plants harness the high temperature and pressure of a geothermal reservoir to generate steam that drives a steam turbine and returns water to the reservoir (DOE, 2012). Binary plants use heat exchangers with a heat exchange fluid to drive a steam cycle (DOE, 2012). Flash steam and binary geothermal power technologies are illustrated in **Figure 1-1**, which shows that the key difference between the technologies is whether or not the fluid from the geothermal formation comes in direct contact with the turbine.

Figure 1-1: Illustration of Common Geothermal Power Technologies (DOE, 2012)



A third type of technology – dry steam geothermal power – uses steam produced directly by the geothermal reservoir to spin a turbine (DOE, 2012). Dry steam fields are rare; the only commercially accessible underground steam source in the U.S. is in Northern California (NREL, 2012).

2 Geothermal Power Technology Performance

Flash steam and binary systems are the two types of geothermal technologies used for new geothermal power projects. Flash steam geothermal plants harness the high temperature and pressure of a geothermal reservoir to generate steam that drives a steam turbine and returns water to the reservoir (DOE, 2012). Binary plants use heat exchangers with a heat exchange fluid to drive a steam cycle (DOE, 2012). Binary systems have lower capacities than flash systems, require the use of a heat exchange fluid, and, since they do not have any steam condensate, must withdraw cooling water makeup from surface water or groundwater sources. This analysis focuses on flash geothermal systems because, while the share of binary geothermal power plants is increasing, over the last 25 years, flash steam geothermal power has been the preferred technology for new geothermal power capacity.[1]

The geothermal power plant of this analysis has a net capacity of 50 MW and is representative of the flash steam geothermal technology. A 50 MW flash steam geothermal power plant consists of 25 production wells, each having a depth of up to two miles. The production wells contain hot water at high pressure; when the water is brought to the surface, it is expanded in a flash vessel to produce steam that is used to drive a steam turbine. Steam condensate from the flash process is used to provide makeup water to the power plant's cooling water system, and thus it is not necessary to withdraw cooling water from other sources. All water that is recovered from the system is returned to the ground using injection wells. A 50 MW geothermal power plant has approximately 10 injection wells.

The expected value capacity factor for geothermal power is 90 percent (EERE, 2006; Tidball, et al., 2010). The capacity factor for geothermal can be as high as 98 percent (EERE, 2006). A low capacity factor of 85 percent is used by this analysis; this low capacity factor is representative of one of the six data sources accounted for by Tidball et al. (2010). The lifetime of a geothermal power plant ranges from 20 to 30 years (Kagel, 2006; Tidball, et al., 2010).

The liquid from a geothermal formation (called "geofluid") contains noncondensible gases such as CO_2, hydrogen sulfide (H_2S), CH_4, and ammonia (NH_3) (Sullivan, Clark, Han, & Wang, 2010). If binary geothermal power technology is used, the geofluid is in a closed system that is reinjected into the ground after all useful energy has been extracted from the geofluid. If flash steam geothermal technology is used, the noncondensible gases are released to the atmosphere. The composition of geofluid is mostly water, but the composition of non-condensible gases is highly variable from one geologic formation to another.

On a volumetric basis, the geofluid in this analysis is 99 percent water, 0.978 percent CO_2, 0.012 percent H_2S, 0.005 percent methane, and 0.005 percent NH_3. Converted to a mass basis, these percentages are 97.6 percent water, 2.4 percent CO_2, 0.022 percent H_2S, 0.004 percent CH_4, and 0.005 percent NH_3 (Bloomfield & Moore, 1999; Bloomfield, Moore, & Neilson, 2003).

To translate the emission of noncondensible gases to the basis of electricity produced, the heat content of the geofluid and performance characteristics of the flash geothermal power plant must be known. No data are available on the average heat content of geofluid; this analysis uses a heat

[1] The installation of binary geothermal power plants began to increase in 2005 and reached a 22 percent share of installed geothermal capacity in 2012.

content of 1,000 Btu per pound, which is comparable to the enthalpy of saturated steam. A 10 MW flash geothermal power plant has a geofluid flow rate of 200,000 pounds (91,000 kg) per hour when operating at full capacity (Bloomfield, 1999). These geofluid and plant performance characteristics are equivalent to a power plant heat rate of 20,000 Btu per net kWh (a 17.1 percent net efficiency). Based on these specifications, the generation of 1 MWh of electricity requires 20,000 pounds (9,070 kg) of geofluid. This quantity of geofluid contains 472 pounds (214 kg) of carbon dioxide as well as other noncondensible gases that are released by the flash process.

The quality of geofluid varies significantly from one geothermal formation to another, making the performance characteristics of geothermal power systems highly variable. To account for this variability, this analysis estimates low and high value parameters for geofluid characteristics and power plant performance. The expected water content of geofluid is 99 percent by volume, but a range in water content from 98 percent to 99.5 by volume is also modeled to account for geothermal formations with different geofluid compositions. The expected value for power plant efficiency is 17.1 percent, and the uncertainty around this efficiency is estimated to range from 10 to 35 percent.

A trunkline is necessary to connect the geothermal power plant to the electricity grid. Depending on the location of the geothermal power plant, the trunkline ranges from 5 to 50 miles in length. A expected trunkline distance of 25 miles is used in this analysis.

The key cost and performance parameters for flash steam geothermal power are shown in **Table 2-1**.

Table 2-1: Performance and Cost Parameters for Geothermal Power

Flash Steam Geothermal Power (All Costs in 2007$)				
Parameter	**Units**	**Low**	**Expected Value**	**High**
Plant Performance				
Plant Capacity	MW_{net}	50	50	50
Net Heat Rate	MJ/kWh_{net}	10.3	21.1	36.0
Net Efficiency	%	10%	17.1%	35%
Capacity Factor	%	85%	90%	98%
Environmental Emissions				
CO_2	kg/MWh	104	214	718
CH_4	kg/MWh	0.19	0.40	1.3
H_2S	kg/MWh	1.0	2.0	6.8
NH_3	kg/MWh	0.21	0.42	1.4
Trunkline Distance	Miles (km)	5.00 (8.05)	25.0 (40.2)	50.0 (80.5)
Economic Performance				
Capital (Power Plant)	2007$/kW	2,000	3,000	5,000
Decommissioning	2007$/kW	209	346	591
Fixed O&M (Annual)	2007$/MW-yr.	82,320	164,600	247,000
Project Life	Years	20	25	30

3 Resource Base and Potential for Growth

In the absence of drilling constraints, if drilled to a sufficient depth, subsurface temperatures at essentially any location in the U.S. could potentially yield geothermal resources sufficient to provide power generation. However, well depth is a key constraint, due to both technological and cost limitations. Therefore, the key determining factor for geothermal resource availability is the proximity of sufficient geothermal resources to the surface. Available geothermal resources are those that are located near enough to the Earth's surface that they can be reached by contemporary drilling techniques, at a cost that is not prohibitive.

The availability of geothermal resources within the U.S. has been studied by the U.S. government, including the Department of Energy and the U.S. Geological Survey, and also by universities and government-university partnerships. As a result, data at the national level for geothermal resource availability are readily available across the U.S. As shown in **Figure 3-1**, the best geothermal resources are available in the U.S. West, including Nevada, Oregon, Idaho, California, Utah, Colorado, New Mexico, Arizona, and Wyoming. Areas with the highest levels of available resource at shallow depths are areas that have favorable conditions including high tectonic heat flow, low thermal conductivity, favorable local conditions, recent volcanic activity, and in some places relatively high crustal radioactivity (INL, 2006).

Assuming that sufficient technologies were to become available to support geothermal resource extraction, the total resource base within the U.S. is enormous. As shown in **Figure 3-2**, at depths of 3.5 to 7.5 km, in the 150 to 250 degrees C range, there is a potential resource base of approximately 13E+18 J. Development of only one percent of this resource would be equivalent to over 1,000 times the annual consumption of primary energy in the U.S. (INL, 2006).

However, achieving development of this resource is the primary concern with respect to the development of geothermal energy. The ability of an existing geothermal resource to be developed can be constrained by various site-specific factors, including the character of geologic formations on site (which can affect cost and feasibility of drilling), temperature and depth of the resource, and the proximity of the resource to available infrastructure, including power lines and supply/access roads. These factors have historically posed significant limitations with respect to the ongoing development of domestic geothermal resources.

Figure 3-1: Domestic Geothermal Resource Availability at 3.5 to 10 km Depth (INL, 2006)

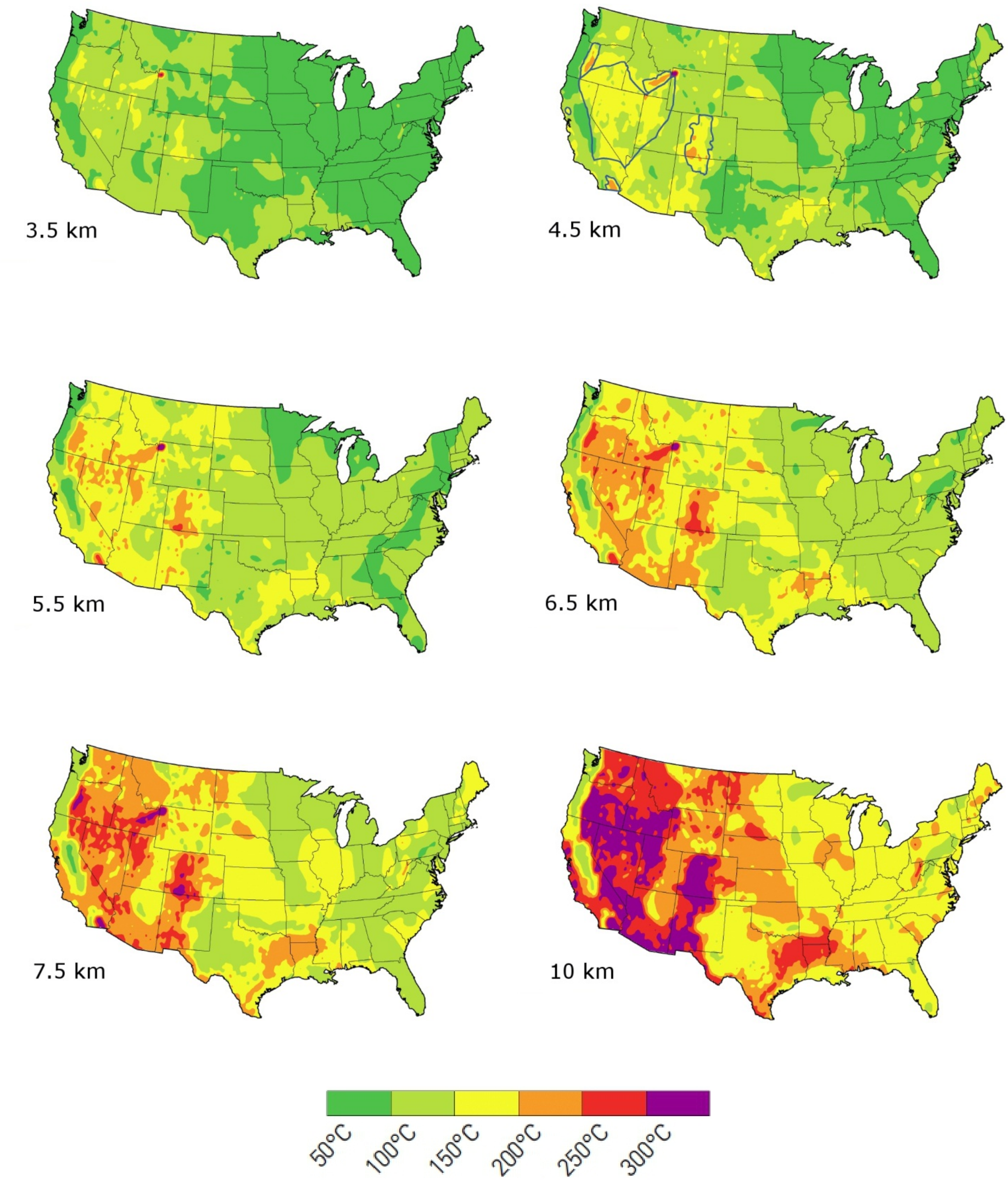
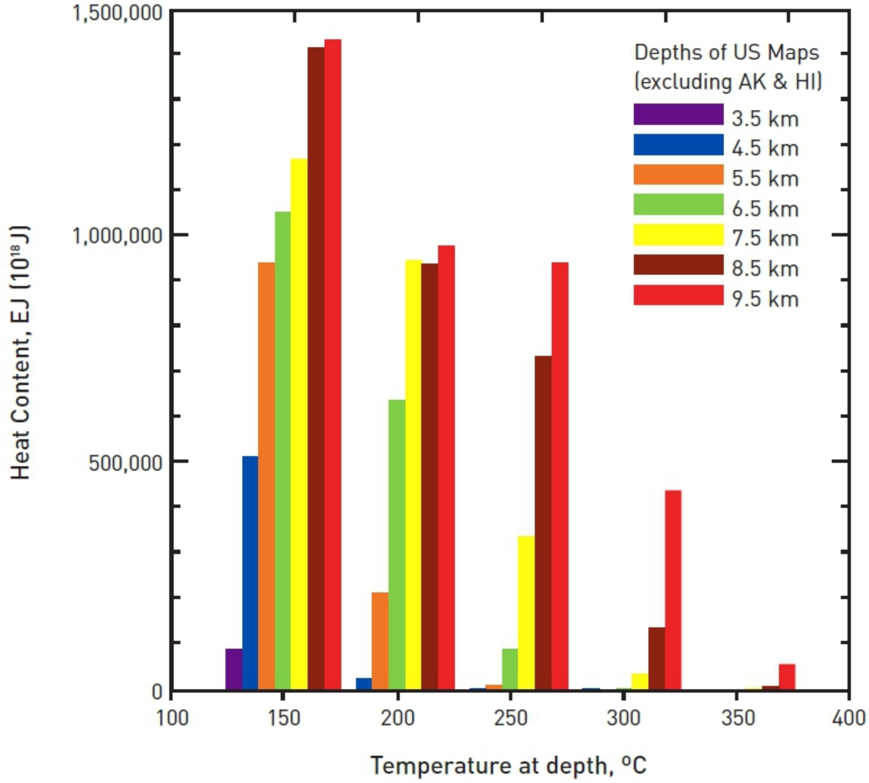


Figure 3-2: Heat Content of the Continental U.S. at 3.5 to 9.5 km Depths (INL, 2006)



The fraction of total U.S. power generation from geothermal power has remained essentially constant since 2000, fluctuating from approximately 0.36 to 0.38 percent, representing a very small portion of total domestic power generation capacity (**Figure 3-3**). Geothermal power production currently lags behind several other renewable power generation sources, including hydroelectric, wind, waste, and wood biomass. However, geothermal power production in 2010 was approximately ten times greater than solar power production (including photovoltaic and solar thermal) (EIA, 2011a).

Dry steam geothermal power represents half of the installed capacity of geothermal power in the U.S., but all viable locations for dry steam have been developed. Since 1985, most of the new geothermal capacity additions used flash steam technology, but in 2005 the share of binary systems began to increase. As of April 2012, dry steam represented 50 percent of installed geothermal capacity (1,585 MW), flash steam represented 28 percent of installed geothermal capacity (900 MW), and binary represented 22 percent of installed geothermal capacity. (GEA, 2012)

Figure 3-4 provides a summary of U.S. geothermal power generation from 2000 through 2010, indicating a modest increase in net generation over time. Overall, geothermal power generation has increased from approximately 14.1 TWh in 2000, to approximately 15.7 TWh in 2010 (EIA, 2011c), equivalent to a compound annual growth rate of only 1.1 percent. This rate of growth represents a lackluster interest in geothermal development over the previous decade, wherein a substantial portion of project expansions were supported, at least in part, by government grants, loan programs, or other public sector incentives.

Figure 3-3: Fraction of 2009 U.S. Electricity Provided by Geothermal (EIA, 2011a)

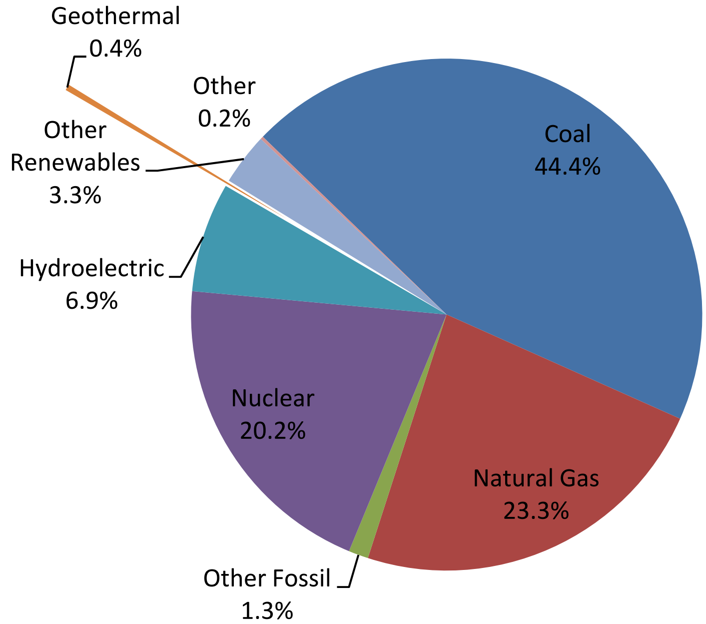
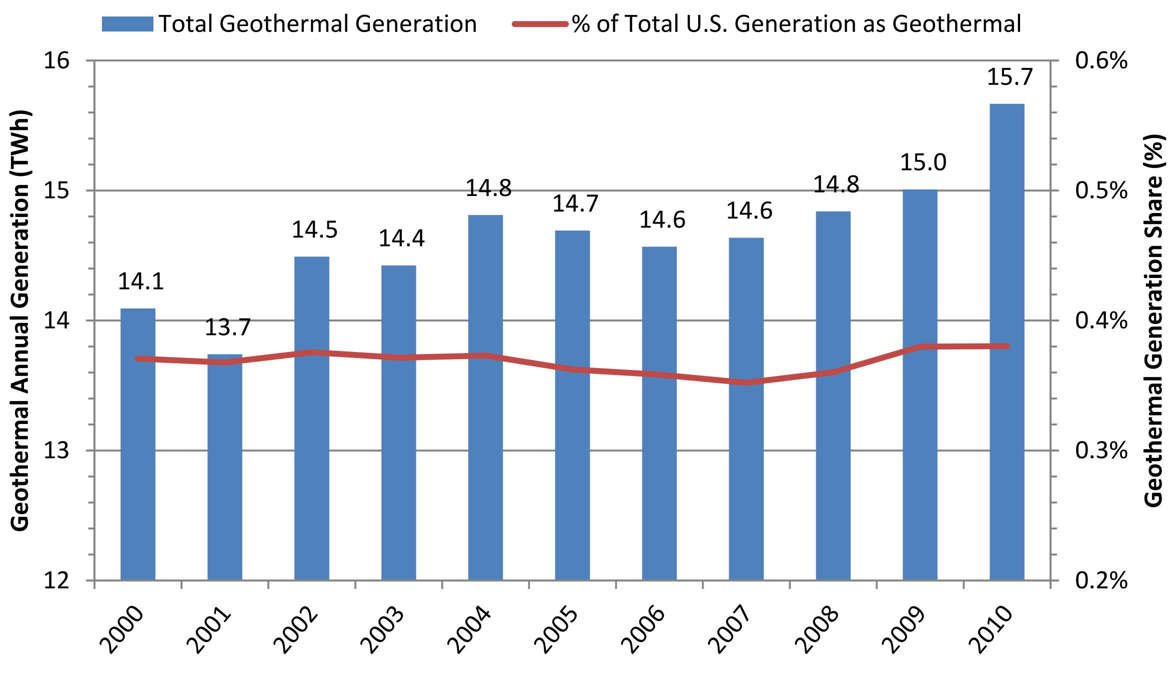
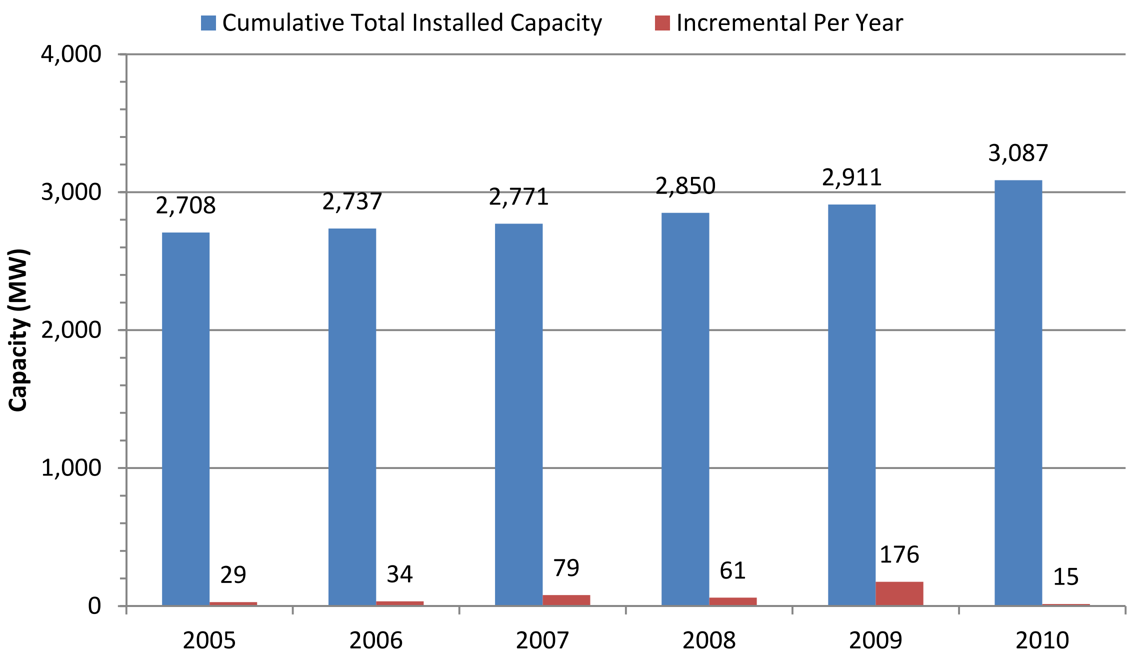


Figure 3-4: Annual Generation and Fraction of Electricity Provided by Geothermal (EIA, 2011b)



While geothermal project installation data from the last 20 years underscore only marginal private sector interest in geothermal energy, more recent trends appear to be supporting resurgence in interest in geothermal energy, balanced with the effects of the global economic turndown. As shown in **Figure 3-5**, installation of new and expanded geothermal facility generation capacity began increasing more rapidly in 2007 through 2009, with new projects and expansions increasing from 34 MW in 2006, to 176 MW in 2009 (GEA, 2011). This is equivalent to a compound annual growth rate in installed capacity of approximately 51 percent, which is high although based on a relatively small total volume. By 2010 the effects of the global economic downturn had significantly impacted geothermal development, resulting in several planned projects being placed on hold.

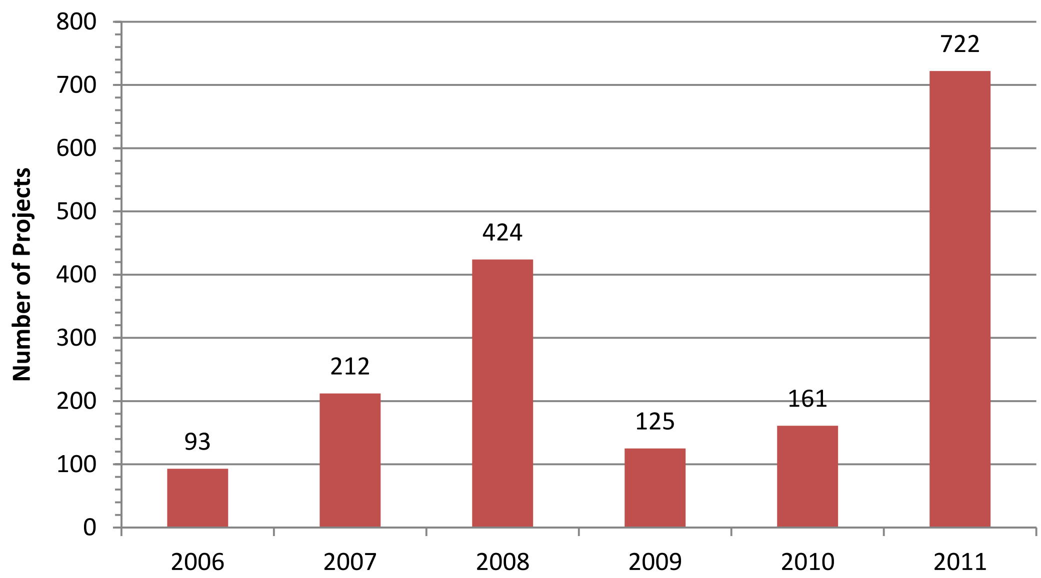
Figure 3-5: Cumulative Total and Incremental Installed Geothermal Capacity (GEA, 2011)



Recent industry geothermal project data support a trend toward increasing geothermal power installations over the ensuing 5 to 10 years. The increase in installed capacity during 2006-2009 shown in **Figure 3-5** is reflected in the number of advanced phase project starts[1] logged during prior years, as shown in **Figure 3-6**. **Figure 3-6** also indicates resurgence in serious interest in new geothermal installations as of the first quarter of 2011, with over 700 advanced implementation phase geothermal projects moving forward. These projects are scheduled primarily for high resource potential areas located in the U.S. West, including California, Nevada, and Oregon. Sharp increases in geothermal power nameplate capacity are expected in those areas over the ensuing 3 to 5 years.

[1] Advanced phase projects are defined here as those that are expected to be installed within 3-4 years.

Figure 3-6: Number of Projects Expected to be Completed Within 3-4 Years (GEA, 2011)



Longer-term installations, beyond 3 to 5 years, are subject to a higher degree of uncertainty than near-term projects. However, the propensity for longer-term installations can be illuminated to some degree by trends in new geothermal projects that have been proposed, but are not yet nearing advanced planning or implementation. **Figure 3-7** provides a breakdown of all known geothermal projects within the U.S. as of April 2011 (GEA, 2011). As shown, 146 proposed geothermal projects have reached at least initial planning and scoping phases. In total these projects represent approximately 1.6 GW of new capacity, equivalent to 53 percent of existing U.S. geothermal capacity as of 2010. Most anticipated projects are planned for Nevada (65 projects totaling approximately 643 MW) and California (30 projects totaling approximately 725 MW), followed by Oregon (9 projects totaling 111 MW). Proposed installations in leading states are supported by renewable portfolio standards, which require that a certain minimum proportion of the state's electricity generation is sourced from renewable power.

The 146 total proposed geothermal projects are overwhelmingly based on conventional geothermal technologies, primarily flash steam and binary. A small number of advanced facilities have also reached at least early planning stages, as shown in **Figure 3-8**. These include enhanced geothermal systems (EGS; essentially deep drilling combined with hydrofracture of the geothermal resource), hydrocarbon coproduction (coproduction of petroleum or natural gas and geothermal resources), and geopressurized systems (utilization of geothermal pressure gradients to generate electricity). Thus, although advanced geothermal technologies, and in particular EGS, have very strong theoretical potential, anticipated installations over at least the next five years are expected to be limited almost exclusively to conventional geothermal technologies.

Figure 3-7: Planned Capacity and Projects, All Known Proposed Projects (GEA, 2011)

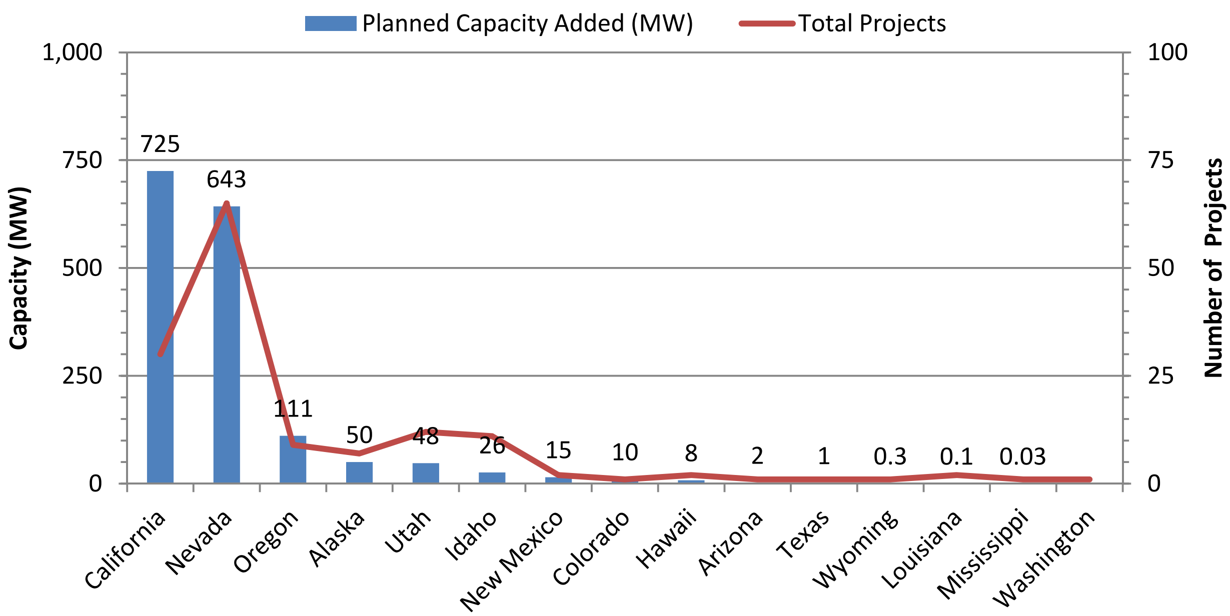
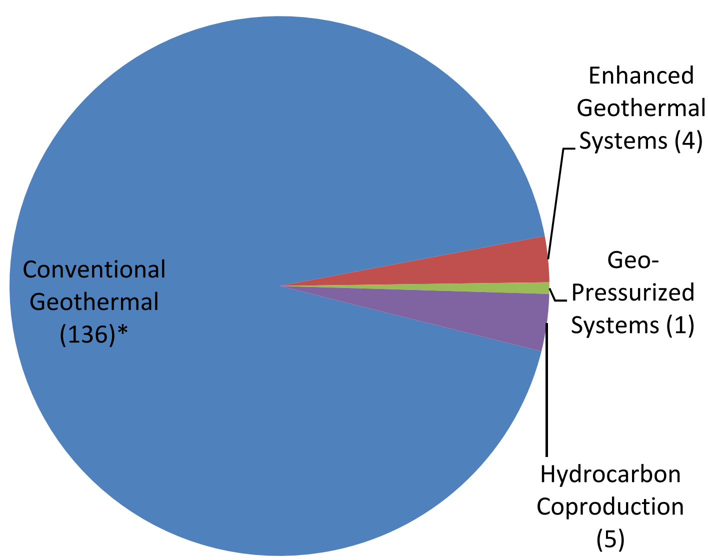


Figure 3-8: Planned Geothermal Technologies for Known Proposed Projects (GEA, 2011)



**Includes flash steam, binary, and dry steam applications*

4 Environmental Analysis of Geothermal Power

The operation of a geothermal power plant does not result in direct emissions of greenhouse gases (GHG) or other air emissions. Further, flash steam geothermal power plants do not withdraw additional water for cooling systems and all excess condensate is returned to injection wells with minimal surface water impacts. However, indirect environmental burdens are associated with the construction and operation of a geothermal power plant. Energy is expended during the manufacture, transport, installation, and maintenance of geothermal equipment; the construction of a trunkline that connects the power plant to the electricity grid also incurs environmental burdens; and air emissions result from the operation of an electricity transmission and distribution network. LCA is necessary to evaluate the environmental burdens from the entire life cycle (LC) of geothermal power.

4.1 LCA Scope and Boundaries

The boundaries of the LCA account for the cradle-to-grave energy and material flows for geothermal power. The boundaries include five LC stages:

LC Stage #1, Raw Material Acquisition (RMA): accounts for acquisition of fuels from the earth or forest. RMA is not relevant to geothermal power because geothermal energy is a natural resource that does not require anthropogenic inputs prior to power generation.

LC Stage #2, Raw Material Transport (RMT): accounts for transport of fuels between acquisition and the energy conversion facility. RMT is not relevant to geothermal power because it uses a natural energy source that does not require anthropogenic inputs prior to power generation.

LC Stage #3, Energy Conversion Facility (ECF): includes the construction and operation of the geothermal power plant and the trunkline that connects it to the electricity grid. The key activities at the geothermal power plant include the drilling of wells with a diesel-powered rig, construction and installation of pipelines used for transporting hot water, construction and installation of power generation equipment, and construction and operation of the electricity trunkline. This stage includes environmental emissions from the power plant; the operation of a flash geothermal power plant that releases noncondensible gases, including CO_2, into the atmosphere.

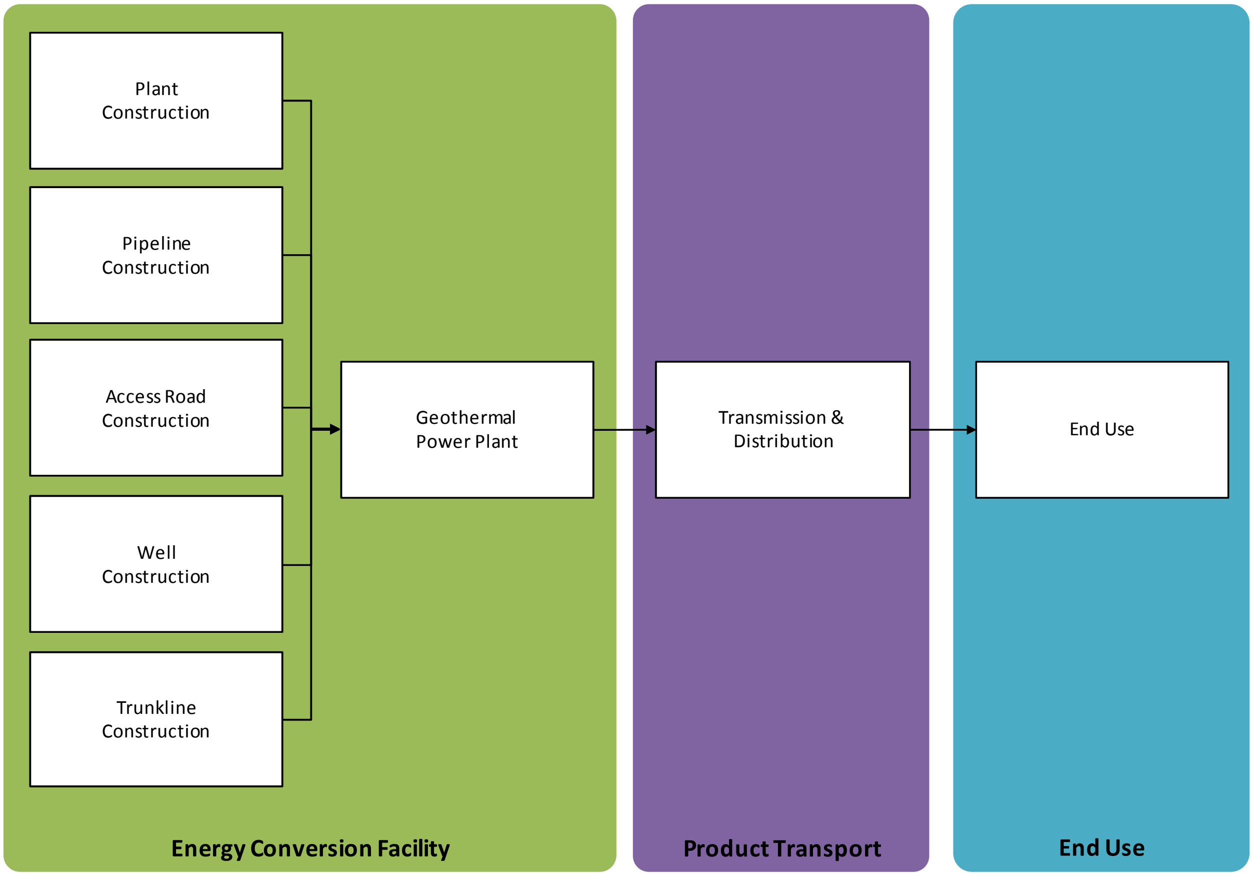
LC Stage #4, Product Transport (PT): accounts for the transmission of electricity from the point of generation to the final consumer. There is a seven percent loss associated with transmission and distribution (T&D) of electricity (representative of the U.S. average electricity grid). The only emission associated with this stage is the sulfur hexafluoride (SF_6) that is released by transmission and distribution equipment.

LC Stage #5, End Use (EU): represents the use of electricity by the consumer. No environmental burdens are incurred during this stage.

The use of a consistent functional unit is a convention that enforces comparability between LCAs. The functional unit of this analysis and other NETL power LCAs is the delivery of one MWh of electricity to the consumer.

An LCA model is an interconnected network of unit processes. The throughput of one unit process is dependent on the throughputs of upstream and downstream unit processes. **Figure 4-1** shows NETL's total LC approach to modeling geothermal power.

Figure 4-1: LCA Modeling Framework for Geothermal Power



GHGs in this inventory are reported on a common mass basis of carbon dioxide equivalents (CO_2e) using the global warming potentials (GWP) of each gas from the 2007 Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (Forster et al., 2007). The default GWP used is the 100-year time frame. For comparison, **Table 4-1** shows the IPCC 2007 GWPs for 20-year, 100-year, and 500-year time frames.

Table 4-1: IPCC 2007 Global Warming Potentials (Forster, et al., 2007)

GHG	20-year	100-year (Default)	500-year
CO_2	1	1	1
CH_4	72	25	7.6
N_2O	289	298	153
SF_6	16,300	22,800	32,600

The results of this analysis also include an inventory of non-GHG emissions, effluents related to water quality, resource consumption, and water withdrawal and discharge. Equivalency factors are not applied to these metrics.

Table 4-2 shows the important parameters used by NETL's LCA model of geothermal power.

Table 4-2: Geothermal Power Modeling Parameters

Parameter	Expected Value	Units
Net Capacity	50	MW
Capacity Factor	90	%
Depth per Well	10,600 (3,230)	Foot (m)
Number of Production Wells	25	Count
Number of Injection Wells	10	Count
Plant Life	25	Years
Trunkline Distance	25.0 (40.2)	Miles (km)

4.2 LCA Data

The LCA model of this analysis uses a screening approach, which means that proxy data were used instead of developing new data specific to geothermal systems. Five key processes are identified for the construction and operation of a flash steam geothermal power plant:

- Well construction and installation
- Power plant construction and installation
- Pipeline construction and installation
- Access road construction
- Trunkline construction and operation

The data used for these five processes are described below.

4.2.1 Well Construction and Installation

The inputs to this unit process are steel pipe and concrete (which are used as casing materials for the well) and diesel (which is combusted in drilling equipment during well installation). The energy and material flows for the upstream production and delivery of steel, concrete, and diesel are not included in this unit process but are accounted for by other unit process. The output of this unit process is the fraction of the well materials and installation energy that is attributable to one MWh of geothermal power. This unit process also accounts for environmental emissions that are directly released by the combustion of diesel during well installation.

4.2.2 Power Plant Construction and Installation

The scope of this unit process covers the construction and installation of a geothermal power plant. The construction and installation of a single natural gas combined cycle (NGCC) power plant was used as a proxy for the geothermal power plant. Inputs to the unit process for the construction of the plant include steel plate, steel pipe, aluminum sheet, cast iron, and concrete. The energy and material flows for the upstream production and delivery of steel, concrete, aluminum, and cast iron are not included in this unit process but are accounted for by other unit process. Diesel, water, and emissions associated with plant installation are also included. The process is based on the reference flow of one piece of geothermal power plant construction and installation per MWh of electricity produced.

4.2.3 Pipeline Construction and Installation

The geothermal facility has a network of pipelines that transports water from wells to the power plant. The total length of this pipeline is 2.42 to 11.3 km (1.50 to 7.00 miles) (BLM, 2008). The pipeline is 24 to 36 inches in diameter (BLM, 2008), and is constructed of steel from the blast furnace process.

4.2.4 Access Roads

The scope of this unit process covers the materials required for the construction of a (linear) meter of gravel road, used on site at a geothermal power plant, to facilitate the use of large/heavy transport trucks and other heavy duty vehicles for well installation and maintenance. The road is assumed to be constructed entirely of gravel. Installation of the road on site is presumed to require conventional diesel fuel for the use of grading and other construction equipment. The process is based on the reference flow of one meter of gravel road per MWh of electricity output from the geothermal power plant.

4.2.5 Power Plant Operation

The liquid from a geothermal formation (called "geofluid") contains noncondensible gases such as CO_2, H_2S, CH_4, and NH_3 (Sullivan, et al., 2010). If binary geothermal power technology is used, the geofluid is in a closed system that is reinjected into the ground after all useful energy has been extracted from the geofluid. If flash steam geothermal technology is used, the noncondensible gases are released to the atmosphere. The composition of geofluid is mostly water, but the composition of noncondensible gases is highly variable from one geologic formation to another.

On a volumetric basis, the geofluid in this analysis is 99 percent water, 0.978 percent CO_2, 0.012 percent H_2S, 0.005 percent methane, and 0.005 percent NH_3. Converted to a mass basis, these percentages are 97.6 percent water, 2.4 percent CO_2, 0.022 percent H_2S, 0.004 percent CH_4, and 0.005 percent NH_3 (Bloomfield & Moore, 1999; Bloomfield, et al., 2003).

To translate the emission of noncondensible gases to the basis of electricity produced, the heat content of the geofluid and performance characteristics of the flash geothermal power plant must be known. No data are available on the average heat content of geofluid; this analysis uses a heat content of 1,000 Btu per pound, which is comparable to the enthalpy of saturated steam. A 10 MW flash geothermal power plant has a geofluid flow rate of 200,000 pounds (91,000 kg) per hour when operating at full capacity (Bloomfield, 1999). These geofluid and plant performance characteristics are equivalent to a power plant heat rate of 20,000 Btu per net kWh (a 17.1 percent net efficiency). Based on these specifications, the generation of 1 MWh of electricity requires 20,000 pounds (9,070 kg) of geofluid. This quantity of geofluid contains 472 pounds (214 kg) of CO_2 as well as other noncondensible gases that are released by the flash process.

The quality of geofluid varies significantly from one geothermal formation to another, making the performance characteristics of geothermal power systems highly variable. To account for this variability, this analysis estimates low and high value parameters for geofluid characteristics and power plant performance. The expected water content of geofluid is 99 percent by volume, but a water content of 98 percent by volume is also modeled to account for geothermal formations with higher quantities of noncondensible gases. The expected value for power plant efficiency is 17.1 percent, and the uncertainty around this efficiency is estimated to range from 10 to 35 percent.

4.2.6 Trunkline Construction and Installation

This unit process provides a summary of relevant input and output flows associated with the construction of a trunkline that connects the geothermal power plant to the main electricity transmission grid. Key components include steel towers, concrete foundations, and steel-clad aluminum conductors. The lifetime electricity throughput of the trunkline is estimated in order to express the inputs and outputs on the basis of mass of materials per one MWh of electricity transport.

4.3 Land Use Change

Analysis of associated land use effects is considered a central component of an LCA under both International Organization for Standardization (ISO) 14044 and American Society for Testing and Materials (ASTM) standards. Additionally, the U.S. Environmental Protection Agency (EPA) released a final version of the Renewable Fuel Standard Program 2 (RFS2) (EPA, 2010b). Included in RFS2 is a method for assessing land use change and associated GHG emissions that are relevant to this LCA. The land use analysis presented in this study is consistent with the method presented in RFS2. It quantifies both the area of land changed, as well as the GHG emissions associated with that change, for direct and select indirect land use impacts.

4.3.1 Definition of Direct and Indirect Impacts

Land use effects can be roughly divided into direct and indirect. In the context of this study, direct land use effects occur as a direct result of the LC processes needed to produce electricity via geothermal power production. Direct land use change is determined by tracking the change from an existing land use type (native vegetation or agricultural lands) to a new land use that supports production.

Indirect land use effects are changes in land use that occur as a result of the direct land use effects. For instance, if the direct effect is the conversion of agricultural land to land used for energy production or conversion, an indirect effect might be the conversion of native vegetation to new farmland, but at a remote location, in order to meet ongoing food supply/demand. This specific case of indirect land use change has been studied in detail by the U.S. EPA (EPA, 2009) and other investigators, and sufficient data are available to enable its consideration within this study. There are also many other types of indirect land use change that could result from installation and operation of new energy production and conversion facilities. For instance, the installation of a large new power generation in a rural location could result in the migration of employees closer to the site, causing increased urbanization in surrounding areas. However, due to high uncertainty in predicting and quantifying this and other less studied indirect effects, only the displacement of agricultural lands resulting in conversion of other land uses to agriculture was considered within the scope of this study.

4.3.2 Land Use Metrics

A variety of land use metrics, which seek to numerically quantify changes in land use, have been devised in support of LCAs. Two common metrics in support of a process-oriented LCA are transformed land area (square meters of land transformed) and GHG emissions (kg CO_2e). The transformed land area metric estimates the area of land that is altered from a reference state, while the GHG metric quantifies the amount of carbon emitted in association with that change. **Table 4-3** summarizes the land use metrics included in this study.

Table 4-3: Primary Land Use Change Metrics Considered in this Study

Metric Title	Description	Units	Type of Impact
Transformed Land Area	Area of land that is altered from its original state to a transformed state during construction and operation of the advanced energy conversion facilities and biomass production	Square Meters (Acres)	Direct and Indirect
Greenhouse Gas Emissions	Emissions of GHGs associated with land clearing/transformation, including emissions from aboveground biomass, belowground biomass, soil organic matter, and lost forest sequestration	kg CO_2e (lbs. CO_2e)	Direct and Indirect

For this study, the assessment of land use GHG emissions includes those emissions that would result from the following, for each LC Stage and direct and indirect GHG emissions as relevant:

- Quantity of GHGs emitted due to biomass clearing during construction of each facility
- Quantity of GHGs emitted due to oxidation of soil carbon and underground biomass following land transformation
- Evaluation of ongoing carbon sequestration that would have occurred under existing conditions, but did not occur, under study/transformed land use conditions

Additional land use metrics, such as potential damage to ecosystems or species, water quality changes, changes in human population densities, quantification of land quality (e.g. farmland quality), and many other land use metrics may conceivably be included in the land use analysis of an LCA. However, data needed to support accurate analysis of these metrics are severely limited in availability (Canals et al., 2007; Koellner & Scholz, 2007), or otherwise outside the scope of this study. Therefore, only transformed land area and GHG emissions are quantified for this study.

4.3.3 Methods

As previously discussed, the land use metrics used for this analysis quantify the land area that is transformed from its original state due to construction and operation of the facilities required for the geothermal case considered in this study. Results from the analysis are presented as per the reference flow for each relevant LC stage, or per MWh when considering the additive results of all stages.

4.3.3.1 Transformed Land Area

The transformed land area metric was assessed using data available from the U.S. Bureau of Land Management (BLM, 2008), based on a programmatic environmental impact statement (EIS) prepared for a geothermal development within the western U.S. The EIS provides land use areas and facilities information based on a 50 MW geothermal power plant footprint, including trunkline. Existing land uses were apportioned according to state level land use data available from the U.S. Department of Agriculture (USDA, 2005). Assumed facility locations are shown in **Table 4-4**. The facility sizes, locations, and other parameters for production of power from geothermal used elsewhere in this LCA were incorporated into the transformed land area metric for consistency. No facilities are required for the study under LC Stages #1 and #2, and it is further assumed that the U.S. power grid system was pre-existing, and no construction or other changes would occur under LC Stage #5 that would be relevant to land use.

Table 4-4: Geothermal Facility Locations

Profile or LC Stage No.	Facility	Location
LC Stage #3: Energy Conversion Facility	Geothermal Wells and Energy Conversion Facility	U.S. West: California, Colorado, Idaho, Montana, Nevada, New Mexico, Oregon, Utah
LC Stage #4: Product Transport	Geothermal Trunkline	U.S. West: California, Colorado, Idaho, Montana, Nevada, New Mexico, Oregon, Utah

For indirect land use change, consistent with EPA's RFS2 analysis, it was assumed that 30 percent of all agricultural land that was lost as a result of the installation of facilities within the study resulted in the creation of new agricultural land at a remote location, within the U.S. The creation of new agricultural land, in turn, was assumed to result in the conversion of either forest or grassland/pasture to farmland, according to regional land use characteristics identified in USDA (2005).

4.3.3.2 Greenhouse Gas Emissions from Land Use Change

GHG emissions due to land use change were evaluated based upon the U.S. EPA's methodology for the quantification of GHG emissions, in support of RFS2 (EPA, 2010b). EPA's analysis quantifies GHG emissions that are expected to result from land use changes from forest, grassland, savanna, shrubland, wetland, perennial, or mixed land use types to agricultural cropland, grassland, savanna, or perennial land use types. Relying on an evaluation of historic land use change completed by Winrock, EPA calculated a series of GHG emission factors for the following criteria: change in biomass carbon stocks, lost forest sequestration, annual soil carbon flux, methane emissions, nitrous oxide emissions, annual peat emissions, and fire emissions, each of which would result from land conversion over a range of timeframes. EPA's analysis also includes calculated reversion factors, for the reversion of land use from agricultural cropland, grassland, savanna, and perennial, to forest, grassland, savanna, shrub, wetland, perennial, or mixed land uses. Emission factors considered for reversion were change in biomass carbon stocks, change in soil carbon stocks, and annual soil carbon uptake over a variety of timeframes. Each of these emission factors, for land conversion and reversion, was included for a total of 756 global countries and regions within countries, including the 48 contiguous states.

Based on the land use categories (forest, grassland, and agriculture/cropland) that were affected by study facilities, EPA's emission factors were applied on a statewide or regional basis. For a more extensive review of the methods used to evaluate GHG emissions from land use change used by EPA for RFS2, please refer to (EPA, 2010b).

GHG emissions from indirect land use were quantified only for the displacement of agriculture, and not for the displacement of other land uses. Indirect land use GHG emissions were calculated based on estimated indirect land transformation values, as discussed previously. Then, EPA's GHG emission factors for land use conversion were applied to the indirect land transformation values, according to transformed land type and region, and total indirect land use GHG emissions were calculated.

4.4 LCA Results

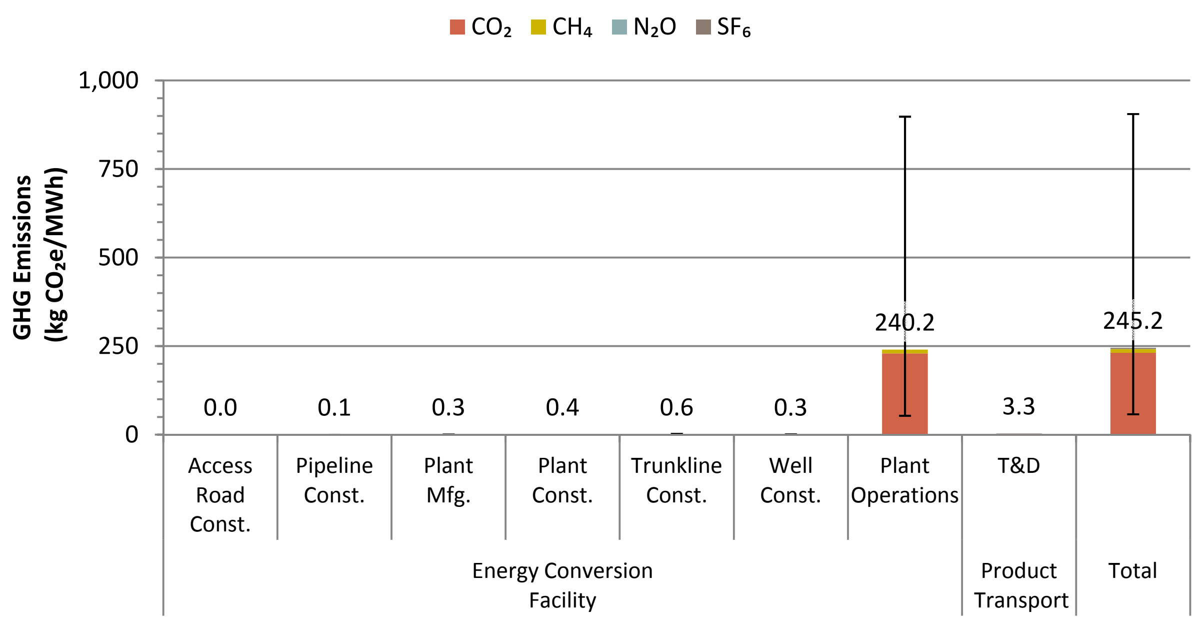
The LCA model of this analysis accounts for the GHG emissions of the LC of geothermal power, including emissions from the construction and installation of geothermal facilities and the transmission and distribution of electricity. All results are expressed on the basis of one MWh of electricity delivered to the consumer.

4.4.1 GHG Results for Geothermal Power

The LC GHG emissions for the geothermal power system in this analysis are 245 kg CO_2e/ MWh. As shown in **Figure 4-2**, the GHG profile for geothermal power is dominated by CO_2 from operation of the geothermal power plant. The main source of these CO_2 emissions is noncondensible gases released by the flash steam geothermal power plant. Water from geological formations (called "geofluid") has naturally-occurring CO_2 and other gases that are released by the flash steam process. The CO_2 emitted by the flash steam geothermal power plant accounts for 93.6 percent of total LC GHG emissions. The expected GHG emissions are 245 kg CO_2e/MWh, but when the uncertainty of all parameters is combined, the GHG emissions range from 57.8 to 906 kg CO_2e/MWh. This wide range of uncertainty is mostly driven by variability in portion of noncondensible gas in the geofluid.

The remainder of the GHG profile for geothermal power includes CO_2 from the installation of the geothermal power plant (including the wells) and supporting infrastructure. Sulfur hexafluoride (SF_6), also a GHG, is released during the operation of the trunkline and during the T&D of electricity.

Figure 4-2: Life Cycle GHG Profile for Geothermal Power



Detailed GHG results for geothermal power are shown in **Table 4-5**. All values are expressed in kg of CO_2e per MWh of delivered electricity. The CO_2e values are calculated from the GHG inventory results using global warming potentials (GWP) of 298 for N_2O, 25 for CH_4, and 22,800 for SF_6.

Table 4-5: Life Cycle GHG Emissions for Geothermal Power (kg CO_2e/MWh)

Stages and Substages		CO_2	CH_4	N_2O	SF_6	Total
Energy Conversion Facility	Access Road Construction	7.64E-04	5.53E-05	6.87E-05	6.37E-12	8.88E-04
	Pipeline	8.85E-02	2.32E-03	1.39E-03	4.45E-11	9.22E-02
	Plant Manufacturing	3.18E-01	9.24E-03	3.42E-03	2.93E-04	3.31E-01
	Plant Construction	4.27E-01	1.21E-02	3.14E-03	3.11E-09	4.42E-01
	Trunkline Construction	5.60E-01	1.99E-02	2.25E-03	1.88E-04	5.83E-01
	Well Construction	2.98E-01	2.65E-03	1.07E-03	4.64E-05	3.01E-01
	Operations	2.30E+02	1.07E+01	0.00E+00	0.00E+00	2.40E+02
Product Transport	Transmission and Distribution	0.00E+00	0.00E+00	0.00E+00	3.27E+00	3.27E+00
Total		**2.31E+02**	**1.07E+01**	**1.13E-02**	**3.27E+00**	**2.45E+02**

The GHG results show that the properties of geofluid (specifically, the composition of noncondensible gases in the geofluid) are the key driver of GHG results and introduce the most uncertainty to this analysis. A sensitivity analysis was performed to further demonstrate the way in which GHG emissions change with changes in key modeling parameters. **Table 4-6** shows the parameters that were evaluated to understand the sensitivity and uncertainty in the LCA model for geothermal power. Parameters include power plant capacity, well depth, plant life, trunkline distance, and geofluid and steam properties.

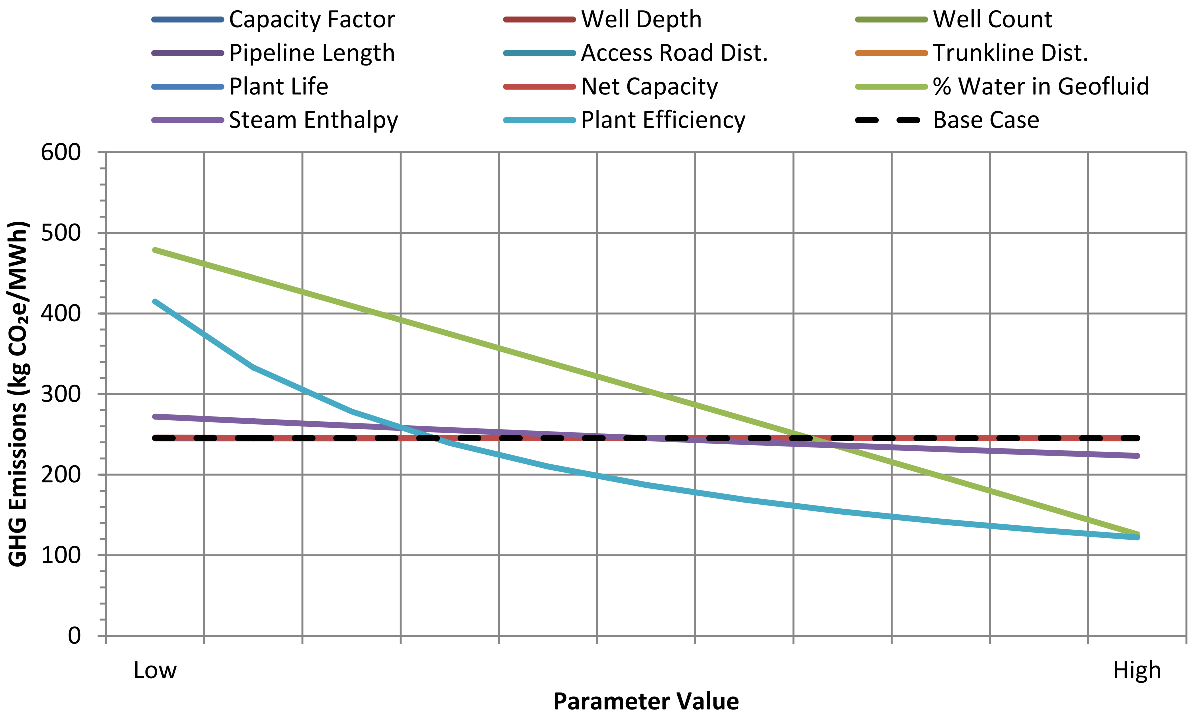
Table 4-6: Geothermal LCA Modeling Parameters

Parameter	Units	Low Value	Expected Value	High Value
Capacity Factor	%	85%	90%	98%
Well Depth	m	2,910	3,230	3,554
Well Count	lb.	15	35	35
Pipeline Length	mi.	1.5	4.25	7
Access Road Distance	mi.	0.5	4.75	9
Trunkline Distance	km	8.05	40.2	80.5
Plant Life	Years	20	25	30
Net Capacity	MW	30	50	50
Volumetric Composition of Water in Geofluid	%	98%	99%	99.5%
Steam Enthalpy	MJ/kg	2.097	2.330	2.563
Plant Efficiency	%	10%	17.1%	35%

Figure 4-3 shows the range of LC GHG emissions for conventional geothermal power as a function of the range of values for the model input parameters shown in **Table 4-6**. The expected base case result of 245 kg CO_2e/MWh is shown for reference as a dashed line. The range in GHG results shown in this figures are from 122 to 479 kg CO_2e/MWh; this range is narrower than the total

uncertainty range shown in **Figure 4-2,** because it isolates the uncertainty to one parameter at a time and does not show the combined uncertainty caused by all parameters.

Figure 4-3: Uncertainty and Sensitivity of Geothermal Power GHG Emissions



The slopes of the lines in **Figure 4-3** indicate the extent to which the GHG results are sensitive to changes in parameters. The steeper a line, the more significant the sensitivity. The two parameters that cause the most sensitivity are the volumetric composition of water in the geofluid and the efficiency of the plant. These two parameters have a strong inverse relationship to the GHG emissions from the system. As the volumetric composition of water in the geofluid and the efficiency of the power plant increase, the GHG emissions per MWh of electricity decrease.

The GHG results are not as sensitive to parameters that are not directly associated with the power output of the geothermal plant. For example, the number and depth of wells drilled for a given power output, the length of pipeline, and the distance of the access road do not significantly impact the LC GHG profile for geothermal power. The enthalpy of steam is important because it is related to the volume of geofluid used by the facility, but it is not as important as the volumetric composition of water in the geofluid or the plant efficiency.

Results from the analysis of transformed land area are illustrated **Figure 4-4**. As shown, geothermal power production results in approximately 0.13 m^2/MWh of transformed land area. Land transformation is caused primarily by transmission line installation (64 percent of total transformed land area), followed by drilling and well field development (13 percent of total), road improvement and construction (8.6 percent of total), power plant construction (6.7 percent of total), and installation of wellfield equipment including pipelines (5.3 percent of total). Total transformed land use for the 50 MW facility was approximately 374 acres. As shown in **Figure 4-4**, based on the facility's location in the Western U.S., existing land uses were primarily grassland and pasture (55 percent), followed by forest (32 percent), and agriculture (12 percent).

Figure 4-4: Direct Land Use, Transformed Land Area

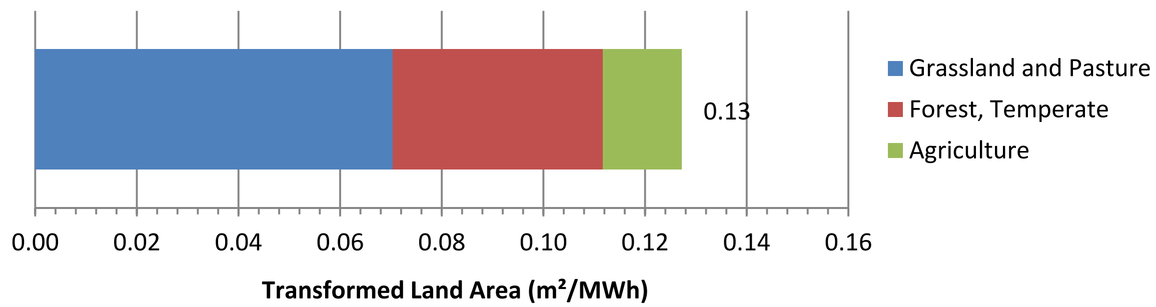
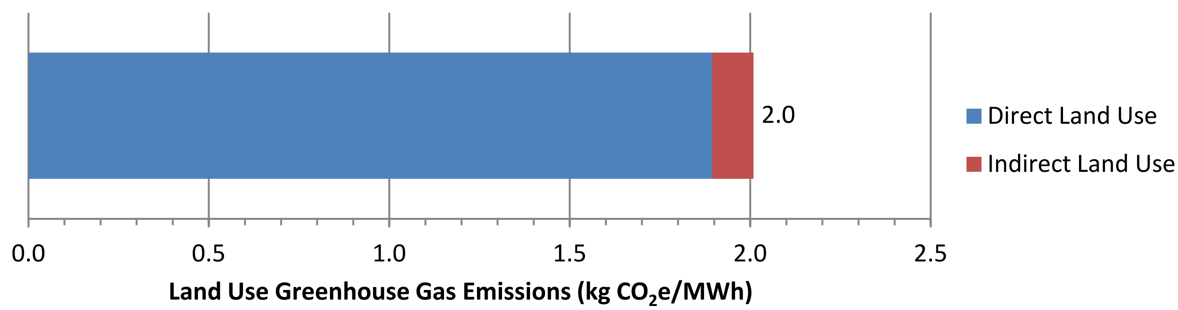


Figure 4-5 shows results from the analysis of GHG emissions from direct and indirect land use. Direct and indirect land use GHG emissions together account for 2.0 kg CO_2e/MWh. Of this total, 94 percent (1.9 kg CO_2e/MWh) results from direct land use, while only 6 percent (0.11 kg CO_2e/MWh) results from indirect land use. Indirect land use is comparatively unimportant due to the low proportion of agricultural use within the geothermal facility's disturbance area. Direct land use GHG emissions result primarily from loss of forestland on site, and to a lesser extent grassland/pasture.

Figure 4-5: Direct and Indirect Land Use GHG Emissions



GHG emissions from land use are small in comparison to other GHG from the LC of geothermal power. The land use GHG emissions from geothermal power increase the total LC GHG emissions from 245 to 247 kg CO_2e/MWh, a 0.8 percent increase.

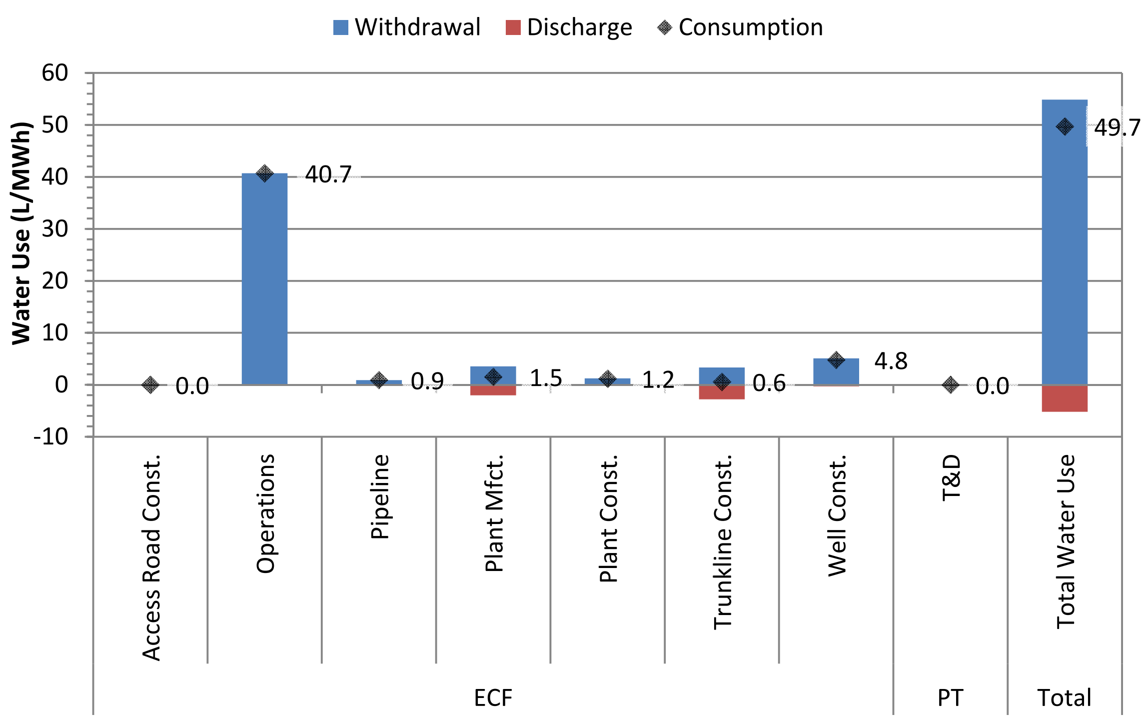
In addition to GHG emissions, this analysis includes an extended set of air and water emissions. **Table 4-7** provides the LC results for a selected group of air pollutants, including criteria air pollutants. This study was not performed as a comparative analysis, so there are no reference values for the emissions to other power generation technologies. Ammonia (NH_3) is a component of the geofluid and is released during the operation of the power plant. The majority of lead and mercury emissions results from the production of steel used for power plant construction. The combustion of fuels for the construction of the geothermal facility produces most of the carbon monoxide (CO) and nitrogen oxide (NO_X) emissions. Other than SF_6, a GHG emission, there are no emissions from transmission and distribution of electricity. The transmission and distribution infrastructure is an existing system, so it does not have any construction burdens within the boundaries of this analysis.

Table 4-7: Other Life Cycle Air Emissions for Geothermal Power (kg/MWh)

Air Emission	ECF							PT
	Access Road Const.	Operation	Pipeline Const.	Plant Mfct.	Plant Construction	Trunkline Construction	Well Construction	T&D
Pb	3.35E-12	0	2.47E-07	4.39E-07	1.64E-09	4.70E-07	1.87E-07	0
Hg	2.78E-13	0	6.53E-09	2.32E-08	1.54E-10	3.58E-09	5.12E-09	0
NH_3	3.66E-07	4.53E-01	2.26E-07	1.12E-07	1.55E-05	1.92E-06	9.14E-09	0
CO	2.68E-05	0	6.23E-04	1.77E-03	1.66E-02	4.63E-03	1.50E-03	0
NO_X	7.80E-05	0	2.00E-04	5.87E-04	6.04E-03	9.52E-04	4.67E-03	0
SO_2	4.79E-07	0	2.34E-04	8.49E-04	3.41E-04	1.46E-03	2.23E-04	0
VOC	2.27E-06	0	2.91E-06	1.99E-05	2.03E-04	9.04E-05	1.24E-04	0
PM	1.67E-04	0	9.50E-05	2.65E-04	1.67E-06	6.93E-04	9.54E-05	0

Figure 4-6 shows the water use associated with geothermal power. Flash steam geothermal power consumes 49.7 liters of water per MWh of delivered electricity. The majority of water consumption (40.7 liters per MWh) occurs during the operation of the power plant and represents the loss of water from the flash process. A significant volume of water (9.0 liters per MWh) is also used during the construction of the geothermal power plant; water is necessary for dust suppression during construction and is also used for the production of construction materials.

Figure 4-6: Water Used by Geothermal Power



The energy return on investment (EROI) was also calculated for geothermal power. EROI is defined as the ratio of usable, acquired energy to energy expended. For the delivery of 1 MWh of electricity from geothermal power, the EROI is 208:1. This high EROI is due to low energy expenditures of the geothermal power; the primary energy source is free.

5 Cost Analysis of Geothermal Power

The life cycle costs (LCC) of geothermal power were calculated by performing a discounted cash flow analysis over the lifetime of a geothermal power plant.

5.1 Geothermal LCC Approach and Financial Assumptions

The LCC analysis accounts for the significant capital and O&M expenses incurred by the geothermal power systems. The LCC calculates the cost of electricity (COE), which is the revenue received by the generator per net MWh during the first year of operation, as well as the levelized cost of electricity (LCOE), which is current-dollar cost based on the discounted cash flows over the entire life of the plant (NETL, 2010a). The COE is the preferred cost metric of NETL's bituminous baseline (NETL, 2010a); however, the LCOE is also calculated in this analysis to provide a basis of comparison against past LCC analyses. The LCC calculations were performed using NETL's Power Systems Financial Model (PSFM), which calculates the capital charge factors necessary for apportioning capital costs per unit of production.

Cash flow is affected by several factors, including cost (capital, operating and maintenance (O&M), replacement, and decommissioning or salvage), book life of equipment, federal and state income taxes, equipment depreciation, interest rates, and discount rates. This costs analysis uses the modified accelerated cost recovery system (MACRS) for apportioning depreciation. O&M costs are assumed to be consistent over the study period except for the cost of energy and feedstock materials determined by EIA.

Capital investment costs are defined as equipment, materials, labor (direct and indirect), engineering and construction management, and contingencies (process and project). Capital costs are assumed to be "overnight costs" (not incurring interest charges) and are expressed in 2007 dollars. Accordingly, all cost data are normalized to 2007 dollars.

The boundaries of the LCC are consistent with the boundaries of the environmental portion of the LCA, ending with the delivery of one MWh of electricity to a consumer. The capital costs for the geothermal power facilities account for all upstream economic activities related to the extraction, processing, and delivery of construction materials. The O&M costs of geothermal power do not require the purchase of a primary fuel, but do account for labor and maintenance costs. Finally, all costs at the geothermal power facility are scaled according to the delivery of one MWh of electricity to the consumer, which includes a seven percent transmission and distribution loss between the power facility and the consumer.

The calculation of LCC also requires the specification of financial assumptions. The expected value case of this cost analysis is a low-risk investor-owned utility with a 50/50 debt to equity ratio, a 4.5 percent interest rate, and an internal rate of return on equity (IRROE) of 12 percent. The low-cost and high-cost cases were modeled by varying the internal rate of return on equity from 6 percent to 18 percent. The financial assumptions for the low-, expected-, and high-cost cases are shown in **Table 5-1**.

Table 5-1: Financial Parameters for Geothermal Power

Financial Parameter	Low Cost Case	Expected Cost Case	High Cost Case
Financial Structure Type	Low-risk Investor-owned Utility with Low Return on Equity	Low-risk Investor-owned Utility	Low-risk Investor-owned Utility with High Return on Equity
Debt Fraction (1 - Equity), %	50%	50%	50%
Interest Rate, %	4.5%	4.5%	4.5%
Debt Term, Years	15	15	15
Plant Lifetime, Years	20	25	30
Depreciation Period (MACRS)	20	20	20
Tax Rate, %	38%	38%	38%
O&M Escalation Rate, %	3.0%	3.0%	3.0%
Capital Cost Escalation During the Capital Expenditure Period, %	3.6%	3.6%	3.6%
Base Year	2007	2007	2007
Required Internal Rate of Return on Equity	6.0%	12%	18%

5.2 Geothermal Power Cost Data

Five sources of geothermal cost data were identified. These data are representative of cost and performance characteristics reported by the Energy Information Administration's (EIA) *Annual Energy Outlook*, the Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE), the National Renewable Energy Laboratory (NREL), and the Geothermal Energy Association. A summary of these five data sources is provided below:

- Cross & Freeman (2009) are the primary authors of the *Geothermal Technologies Market Report*, published by the Department of Energy Office of Energy Efficiency and Renewable Energy (EERE). The report includes a survey of geothermal capital costs derived from recent geothermal literature.
- In 2006 EERE published a fact sheet that answered common frequently asked questions (FAQs) about geothermal power (EERE, 2006). The factsheet includes capital cost and O&M costs for geothermal power.
- *Guidebook to Geothermal Power Finance* (Salmon, Meurice, Wobus, Stern, & Duaime, 2011) includes capital cost data for geothermal power. The report was published by the National Renewable Energy Laboratory (NREL) and the cost data in the report were derived from other authors already identified in this analysis.
- *A Handbook on the Externalities, Employment, and Economics of Geothermal Energy* (Kagel, 2006) is the only source of cost data identified during this analysis that was not published by a government entity. It is based on data collected by the Geothermal Energy Association and provides a capital cost range for geothermal power.
- *Cost and Performance Assumptions for Modeling Electricity Generation Technologies* (Tidball, et al., 2010) includes cost data for key renewable energy technologies and compares

them to fossil and nuclear technologies. It compares the geothermal capital costs reported by six data sources and also reports fixed O&M costs.

The following sections describe the calculation of capital, decommissioning, and O&M costs for geothermal power.

5.2.1 Capital Costs

The five sources of cost data identified by this analysis were developed using similar data sources and thus the cost data from these five sources are in close agreement. However, it would not be appropriate to average the capital cost data from the five data sources to arrive at the expected capital costs for this analysis. Tidball et al. (2010) is the most comprehensive source of geothermal cost data, so the range of geothermal capital costs reported by Tidball et al. are used for the cost model of this analysis. The capital costs reported by Tidball et al. range from $2,000/kW to $5,000/kW and have a expected cost of $3,000/kWh. These costs are in 2007 dollars.

Power lines are required to connect the geothermal power plant to the electricity grid. This collection of power lines along with the associated supports and foundations are referred to as a trunkline. The general EIS for geothermal power (BLM, 2008) specifies a trunkline distance of 5 to 50 miles. This analysis uses 5 miles as the low value for trunkline distance, 25 miles as a expected trunkline distance, and 50 miles as the high value for trunkline distance. At a per-mile cost of $912 thousand, a 5-mile trunkline is $4.56 million, a 25-mile trunkline is $22.8 million, and a 50-mile trunkline is $45.6 million.

5.2.2 Decommissioning

This analysis estimates that the cost of decommissioning geothermal power plants is 10 percent of the capital costs of initial construction. Decommissioning requirements are site specific and vary from one power plant to another (IFC, 2007). The closure of a geothermal facility includes the capping of wells, removal of above-ground equipment, contouring of earth, and revegetation (TEEIC, 2011). The required activities for the decommissioning of a geothermal power plant are similar to those of construction and operation, but are of a shorter duration (TEEIC, 2011). The cost model of this analysis capitalizes decommissioning costs, but does not consider them a depreciable asset.

5.2.3 O&M Costs

The expected value fixed O&M costs for geothermal power are $164.6/kW (Tidball, et al., 2010). An uncertainty of +/- 50 percent was assigned to the expected value cost based on O&M cost ranges provided by EERE (2006). Applying this uncertainty range to the expected value gives a low fixed O&M cost of $82.32/kW and a high fixed O&M cost of $247/kW. (These costs are reported in 2007 constant dollars.) Fixed O&M costs account for the majority of O&M costs of geothermal power; none of the data sources include variable O&M costs.

This analysis converts all O&M costs to a 2007 dollar basis using an annual inflation rate of three percent. The capital, decommissioning, and O&M costs for geothermal power are shown in **Table 5-2.**

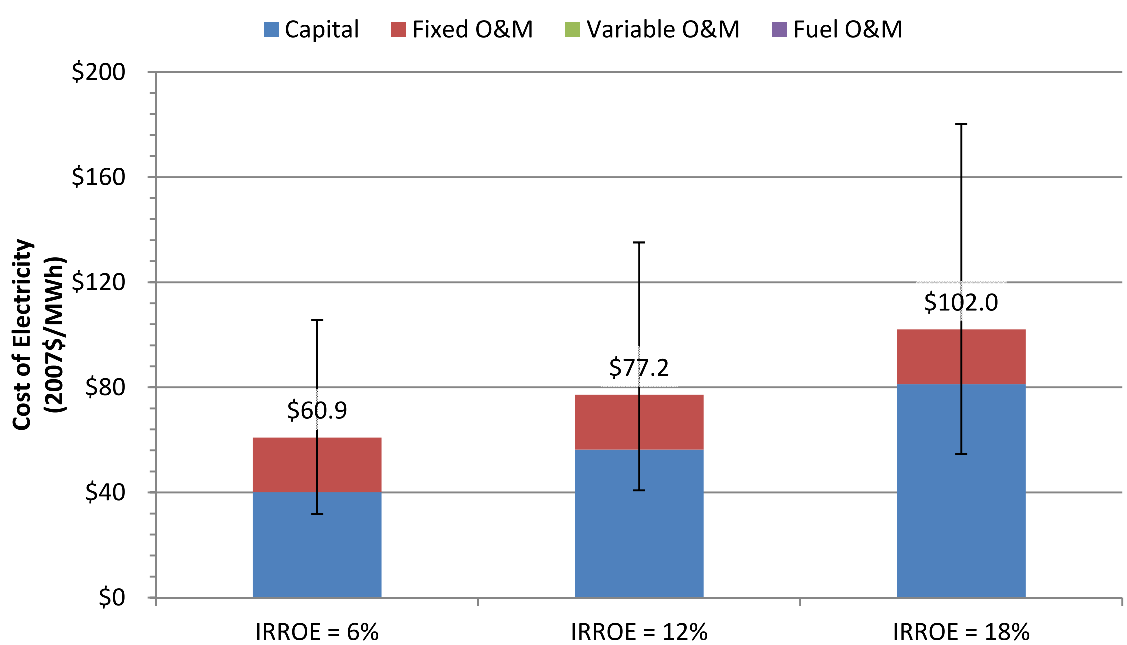
Table 5-2: Cost Summary for Geothermal Power

Parameter	Units	Low Cost Case	Expected Cost Case	High Cost Case
Capital (Power Plant)	2007$/kW	2,000	3,000	5,000
Capital (Trunkline)	2007$/kW	91.2	456	912
Decommissioning	2007$/kW	209	346	591
Variable O&M (Grid Integration)	2007$/MWh	N/A	N/A	N/A
Fixed O&M (Annual)	2007$/MW-yr.	82,320	164,640	246,960
Plant Life	Years	30	25	20
Net Plant Capacity	MW	50	50	50
Capacity Factor	%	98.0%	90.0%	85.0%

5.3 Geothermal LCC Results

The expected COE from geothermal power is $77.2/MWh, as shown in **Figure 5-1**. This value is representative of the expected value financial assumptions shown in **Table 5-1** and the expected value cost parameters shown in **Table 5-2**. It accounts for a seven percent electricity loss during transmission and distribution and is expressed in 2007 dollars.

Figure 5-1: Life Cycle COE of Geothermal Power



Geothermal power does not require the purchase of fuel and thus the O&M costs for geothermal power are low in comparison to power technologies that use fossil fuel or other non-renewable energy sources. Capital costs dominate the COE for geothermal power, comprising 72.95 percent of the COE of geothermal power.

The cost characteristics of geothermal power, like other renewable energy technologies, are site specific, which contributes to the uncertainty in COE. The uncertainty in COE for geothermal power includes ranges in capital costs, plant lifetimes, O&M costs, and capacity factors. When all of these parameters are adjusted to a best case cost scenario, the COE for geothermal power is $40.84/MWh. When all of these parameters are adjusted to a worst case cost scenario, the COE for geothermal power is $135.2/MWh. These low and high results represent extreme cases, but indicate the sensitivity of COE to changes in key cost parameters.

This analysis uses the IRROE as a parameter for modeling financial risk scenarios. The expected value IRROE is 12 percent. However, if investors consider geothermal power a low-risk proposition, then the IRROE could be as low as 6 percent. Conversely, if investors consider geothermal power a high-risk proposition, then the IRROE could be as high as 18 percent. **Figure 5-1** shows the effect of IRROE on the COE of geothermal power. The three scenarios in **Figure 5-1** show an IRROE of 6, 12, and 18 percent; the error bars for each scenario represent the low and high parameters as shown above in **Table 5-2**.

This analysis uses COE as the default metric for the cost of electricity. The levelized cost of electricity (LCOE) is another cost metric, used by past NETL LCAs. The LCOE of geothermal (at a 12 percent IRROE) is $95.88/MWh.

6 Barriers to Implementation

Key barriers to the implementation of geothermal power include resource availability and associated technological and cost constraints. Connecting geothermal facilities to the electricity grid is another barrier to implementation.

6.1 Resource Availability, State of Geothermal Technology, and Cost

As discussed previously, resource availability depends on accessibility of the potential resource, the temperature of the potential resource, and the depth of the potential resource. Readily available surficial geothermal resources, such as those available at The Geysers geothermal complex (located north of San Francisco, CA) are easy to capture and utilize for power generation. However, easily accessible near-surface resources are extremely rare. The Geysers is a particularly exceptional example. Based on a dry steam resource (steam is produced directly from the resource), it is the largest geothermal field in the world, and has a total nameplate capacity of 1.5 GW, with a typical capacity factor of around 60 percent (~950 MW). Most other potential geothermal fields, known to be accessible with currently available technologies and at reasonable cost, are remotely located and have much smaller potential.

Binary plants do not run water from a geothermal well directly through a steam turbine, but use heat exchangers with a closed loop of heat transfer fluid to extract energy from a geothermal well. As shown in **Table 6-1**, binary plants can be engineered to utilize relatively low-temperature geothermal resources, depending upon ambient conditions. However, the amount of power generated by a low-temperature system can be substantially less than a higher-temperature system. This limits the revenue generated by the plant, and thereby limits the cost of infrastructure that can be installed in support of such a project, which in turn limits the amount of money that can be invested in drilling a well that is deep enough to reach the geothermal resource. For instance, capital costs for a binary geothermal facility can range from approximately $1,750 to $4,095/kW, based largely on well depth, the number of wells that would be required to extract the resource, and the total heat output available from the geothermal source (IEA/NEA, 2010).

Table 6-1: Conventional Geothermal Technologies: Standard Minimum Operating Temperatures

Technology	Minimum Operating Temperature (Degrees C)
Dry Steam	150 (Steam)
Flash Steam	182 (Water)
Binary	57* (Water)

** The coolest operating binary plant is the Chena Hot Springs plant in Alaska, with an operating temperature of 57 degrees Celsius. Most currently operating binary plants utilize resources of at least 80-100 degrees Celsius.*

Geothermal well drilling costs can be substantial and commonly constitute one third to one half of total overnight capital costs for a new geothermal plant. Well drilling costs are driven by the specific characteristics of the geothermal system being exploited (EERE, 2006; IEA/NEA, 2010). Deeper wells are, of course, more costly. However, many geothermal resources are located in granitic, basaltic, or other hard rock formations. These formations are physically hard to drill through. Also, geothermal resources are commonly available along deep rock fracture lines. Accessing a suitably sized network of such fractures is required to enable extraction of sufficient heat from the system. However, there is no guarantee that a given well will sufficiently intersect a fracture network, and several wells (injection and extraction) may be needed for a single power plant. Advanced technologies such as enhanced geothermal systems (EGS) promise high generation potential based on a theoretically large resource base. To date, however, EGS has been proposed only in a handful of locations, due to cost and technological constraints, where drilling cost is often the primary constraint.

6.2 Grid Connection

Availability of power transmission capacity, combined with the difficulty of constructing long distance power transmission lines, is another key barrier to the implementation of geothermal power. As shown in **Figure 3-1**, the best geothermal resources are in many cases located far from existing population centers, and distant from existing power transmission lines needed to carry energy onto the power grid. For instance, quality geothermal resources are located throughout much of the sparsely populated Rocky Mountain region. However, achieving reasonable access to potential sites and connecting to existing transmission lines are major barriers to the implementation of additional geothermal capacity. As a result, many high quality geothermal resources in the U.S. West are expected to remain untapped for the foreseeable future, for the simple reason that new transmission facilities are (1) expensive to construct and (2) difficult to permit (Smith & Bruvsen, 2010). For remote geothermal resources, sharing transmission line construction and permitting efforts among many facilities, or with other renewables projects, may be the only workable scenario. However, implementing such agreements requires long-term planning due to long lead times for major transmission facility permitting and installation requirements; therefore, such agreements are difficult to reach and administer.

7 Risks of Implementation

The most common public objections to geothermal installations are potential interference with aesthetic resources and water resources. The programmatic EIS prepared in support of the Bureau of Land Management's land leasing program indicated the following potential environmental impacts associated with geothermal implementation (BLM, 2008):

- Long-term visual degradation from plant installation and operation
- Groundwater impacts during construction
- Long-term loss of vegetation, habitat, and soil
- Short-term intermittent construction impacts, including noise and air emissions
- Potential loss of some recreational opportunities

Long-term degradation of groundwater quality due to geothermal power production has not been widely documented. However, short-term groundwater degradation may occur during the construction process. Various activities including well drilling and water or steam extraction can potentially cause degradation of groundwater quality, by facilitating mixing of (typically poor quality) geothermal water with water contained in overlying aquifers. However, this type of contamination can be prevented by implementing proper management techniques (EPA, 2010a).

There is also a growing public awareness regarding potential for induction of seismic activity due to geothermal power production, especially for EGS technologies. For instance, the hydraulic fracturing of a deep aquifer in Basel, Switzerland, in 2006 generated approximately 30 minor earthquakes, up to 3.4 on the Richter scale (Svoboda, 2010). Potential for induced seismicity is the greatest in areas of existing faulting (which is relatively common in areas with geothermal resources), and for installations of EGS systems. For EGS, water forced under pressure deep underground can trigger seismicity. Increased seismicity has also been observed at The Geysers, and at other existing geothermal facilities globally. A preliminary review identified seismic activity up to about 4.3 on the Richter scale, although theoretically larger magnitude quakes could potentially be induced if a geothermal plant is installed/operated in close proximity to a large fault system. However, a review of available permitting documentation, including public comments on environmental studies, indicated that this is not a key area of public concern for most projects.

Compared with hydropower and solar, geothermal has a comparatively small land area footprint, for most installations. Footprints for geothermal facilities are expected to be similar to wind facilities that are located in mountainous areas, wherein a network of roads would need to be installed to reach various power production and transmission facilities distributed across a thermally active region.

Water use can be a substantial component of some geothermal installations. Depending on reservoir characteristics, some geothermal applications will require the injection of additional water in order to maintain heat production levels sufficient to drive the power plant (BLM, 2008). Substantial volumes of water are also used during well testing, which may require the injection of water to evaluate connectivity with other wells and suitability of the reservoir for power production (BLM, 2008). Closed loop geothermal systems vary in their design, but many require additional cooling cycle water. This water may be supplied from a surface or groundwater supply, or by other water that is available in the vicinity of the plant. Finally, where municipal or other groundwater users are located nearby, activities in the geothermal aquifers may contribute to changes in water quality or availability in other connected aquifers, which may be used for water supply or other beneficial use.

Geothermal resources can also decrease in quality over time. As heat is extracted from the resource, if natural replenishment does not meet the rate of extraction, a gradual net decrease in heat value can occur over time. This could potentially result in a partial reduction in power production capacity. In terms of long-term resource sustainability, degradation due to power production appears to be less of a concern. According to a geothermal trade association, a geothermal project showing a capacity decline after 30 years of operation will restore itself after a century of inactivity (GEA, 2008). Thus, there is some interim risk in loss of capacity, but less long-term risk in terms of resource availability and sustainability.

8 Expert Opinions

Many geothermal industry players are currently expressing positive forecasts (and some extremely positive forecasts) for geothermal power production. The surge in optimism comes after decades of sluggish interest in geothermal energy, and has been driven by recent pilot scale applications of new technologies (EGS, hydrocarbon coproduction, and geo-pressurized systems), as well as discovery of new potentially exploitable resources. One example of a recently-discovered geothermal resource includes an approximately 180 degrees C formation, found in 2010 in West Virginia, at a depth of 3.9 km, that is theoretically capable of supporting nearly 19 GW of new geothermal power capacity (WVU, 2011). Coproduced hot water from petroleum and natural gas has also led to a number of oil and gas geothermal projects or project starts in Texas, Louisiana, Mississippi, and North Dakota (TG, 2010).

A panel of experts led by the Massachusetts Institute of Technology (MIT) recommends large-scale development of EGS in the U.S. These experts argue that EGS is inexpensive compared to conventional fuels used for electricity generation. They also argue that the environmental impacts of EGS development are lower than conventional power plants. However, they also acknowledge some obstacles to the implementation of EGS. Their key concerns include the water requirements and seismic risks of geothermal power. (INL, 2006)

Experts also acknowledge that the future of geothermal power depends on investments that encourage research and enable the startup of new geothermal power installations (INL, 2006). Geothermal power production has also been the benefactor of several new research, development, and demonstration projects, including nearly $450 million combined investment from the American Recovery and Reinvestment Act of 2009, and from the U.S. Department of Energy’s (DOE) Geothermal Technologies Program. Investment tax credits for geothermal were also extended through 2016 (DOE, 2011). These investments seek to partially counter the effects of a prior freeze in global credit and equity availability following the global economic downturn, which made financing of geothermal projects extremely difficult (NREL, 2010) and led to a sharp reduction in new geothermal installations by 2009.

There is also significant interest and publicity surrounding ongoing and anticipated developments with respect to EGS. According to the U.S. Geological Survey (2008), there are sufficient deep geothermal resources in the U.S. to provide over 517 GW of power production capacity. However, EGS is a nascent technology, and is still under development. A report by the Massachusetts Institute of Technology (MIT, 2006) estimates that full-scale implementation will not begin to occur for another 15 years.

9 Summary

This analysis provides insight into the role of geothermal power as a future energy source in the U.S. The criteria used for evaluating the role of geothermal power are as follows:

- Resource base
- Growth
- Environmental profile
- Cost profile
- Barriers to implementation
- Risks of implementation
- Expert opinions

The U.S. has a large **resource base** of geothermal energy, but there are barriers to developing this resource. Assuming that sufficient technology is, or were to become, available to support geothermal resource extraction, the total resource base within the U.S. is enormous. Development of only one percent of this resource would be equivalent to over 1,000 times the annual consumption of primary energy in the U.S. (INL, 2006). However, the harnessing of a geothermal resource is constrained by several factors, including the character of geologic formations on site (which can affect cost and feasibility of drilling), temperature and depth of the resource, and the proximity of the resource to available infrastructure, including power lines and supply/access roads. These factors have historically posed significant limitations with respect to the ongoing development of domestic geothermal resources.

Geothermal power has not exhibited significant **growth** within the last decade. The fraction of total U.S. power generation from geothermal power has remained essentially constant since 2000, fluctuating from approximately 0.36 to 0.38 percent, representing only a very small portion of total domestic power generation capacity. Recent trends indicate resurging interest in geothermal energy; the installation of new and expanded geothermal capacity increased from 2007 through 2009, with new projects and expansions increasing from 34 MW in 2006, to 176 MW in 2009 (GEA, 2011). However, any investments in geothermal and other alternative energy technologies are tempered by the current global economic downturn.

The **environmental profile** focuses on the LC GHG emissions of geothermal power using flash steam technology. The LC GHG emissions for the geothermal power system in this analysis are 245 kg CO_2e/MWh. The GHG profile for geothermal power is dominated by CO_2 emissions. The main source of these CO_2 emissions is noncondensible gases released by the flash steam geothermal power plant. Water from geological formations (called "geofluid") has naturally-occurring CO_2 and other gases that are released by the flash steam process. The CO_2 emitted by the flash steam geothermal power plant accounts for 93.6 percent of total LC GHG emissions. The expected GHG emissions are 245 kg CO_2e/MWh, but when the uncertainty of all parameters is combined, the GHG emissions range from 57.8 to 906 kg CO_2e/MWh. This wide range of uncertainty is mostly driven by variability in portion of noncondensible gas in the geofluid. This analysis accounts for uncertainties in other parameters, such as plant life, number of wells per unit of power plant capacity, distance of access roads, and well depth; the GHG results of the analysis are more sensitive to changes in geofluid composition than to other parameters. The GHG results are also sensitive to changes in power plant efficiency, which is related to the amount of geofluid used by the system.

The results in the above paragraph do not account for the GHG emissions from land use change. The GHG emissions from direct and indirect land use change range are 2.00 kg CO_2e/MWh. The land use GHG emissions for geothermal power increase the total LC GHG emissions by only 0.8 percent.

The **cost profile** of geothermal power is based on a discounted cash flow model that accounts for the significant capital and O&M costs incurred during the LC of geothermal power. The expected value capital costs for a geothermal power plant are $3,000/kW and the expected value O&M costs for geothermal power are $164,600/MW-year (Tidball, et al., 2010). COE (cost of electricity) is the key cost metric of this analysis and represents the revenue received by the generator per net MWh during the first year of operation (NETL, 2010b). The expected value COE for geothermal power is $77.19/MWh (in 2007 dollars), and is representative of a low-risk investor-owned utility with a 50/50 debt to equity ratio, a 4.5 percent interest rate, and an IRROE of 12 percent, and a seven percent electricity loss during transmission. The uncertainty in COE for geothermal power includes ranges in capital costs, plant lifetimes, O&M costs, and capacity factors. When all parameters are adjusted to a best case cost scenario, the COE for geothermal power is $40.84/MWh; when all parameters are adjusted to a worst case cost scenario, the COE for geothermal power is $135.2/MWh. These low and high results demonstrate the sensitivity of COE to changes in key cost parameters.

Key **barriers** to the implementation of geothermal power include resource availability and associated technological and cost constraints. In many cases, a promising geothermal resource may within close proximity of a grid connection, but it is located under a hard rock formation that is difficult and costly to drill.

The **risks of implementation** include public objections based on the potential interference with aesthetic resources and water resources. Aesthetic issues are a matter of perception and are difficult to address. Long-term degradation of groundwater quality due to geothermal power production has not been widely documented. However, short-term degradation may occur during the construction process. There is also a growing public awareness regarding potential for induction of seismic activity due to geothermal power production.

Expert opinions include the outlook of geothermal industry players, who are currently expressing positive forecasts for geothermal power production. The surge in optimism comes after decades of sluggish interest in geothermal energy, and has been driven by recent pilot scale applications of new technologies as well as discovery of new potentially exploitable resources.

Geothermal power is a proven technology with a large resource base, and the use of flash steam technology has relatively low capital costs that translate to a competitive COE. However, the characteristics of geologic formations are highly variable and are a barrier to broad implementation of geothermal power. Further, the naturally-occurring CO_2 in geofluid leads to relatively high GHG emissions from geothermal power plants that use flash steam technology. In order for geothermal power to be a significant part of U.S. electricity generation, research and development efforts must find ways of cost-effectively mitigating the variability among geothermal formations and using energy conversion technologies that reduce (or prevent) the emission of CO_2 from geofluid.

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Appendix A
Constants and Unit Conversion Factors

List of Tables

Table A-1: Common Unit Conversions

Category	Input			Output	
	Value	Units		Value	Units
Mass	1	lb.	=	0.454	kg
	1	Short Ton	=	0.907	Tonne
Distance	1	Mile	=	1.609	km
	1	ft.	=	0.305	m
Area	1	$ft.^2$	=	0.093	m^2
	1	Acre	=	43,560	$ft.^2$
Volume	1	Gallon	=	3.785	L
	1	$ft.^3$	=	28.320	L
	1	$ft.^3$	=	7.482	Gallons
	1	m^3	=	35.3	$ft.^3$
Energy	1	Btu	=	1,055.056	J
	1	MJ	=	947.817	Btu
	1	kWh	=	3,412.142	Btu
	1	MWh	=	3,600	MJ

Table A-2: IPCC Global Warming Potential Factors (Forester, et al., 2007)

IPCC GWP Factor	Vintage	20 Year	100 Year	500 Year
CO_2	2007	1	1	1
CH_4	2007	72	25	7.6
N_2O	2007	289	298	153
SF_6	2007	16,300	22,800	32,600
CO_2	2001	1	1	1
CH_4	2001	62	23	7
N_2O	2001	275	296	156
SF_6	2001	15,100	22,200	32,400

Appendix B
Data for Geothermal Power Modeling

List of Tables

LC Stage #1 or RMA (raw material acquisition) is not relevant to geothermal power because geothermal energy is a natural resource that does not require anthropogenic inputs prior to power generation. LC Stage #2 or RMT (raw material transport) is not relevant to geothermal power because it uses a natural energy source that does not require anthropogenic inputs prior to power generation.

The steady state operation of the flash steam geothermal power plant does not use any purchased fuels or result in direct environmental emissions; thus, this analysis does not have a unit process for the operation of a geothermal power plant.

The LCA model of this analysis uses a screening approach, which means that proxy data were used instead of developing new data specific to geothermal systems. Five key existing unit processes were identified for the construction and operation of a flash steam geothermal power plant:

- Well construction and installation (NETL, 2010a)
- Power plant construction and installation (NETL, 2010b)
- Pipeline construction and installation (NETL, 2010c)
- Trunkline construction and operation (NETL, 2010d)
- Access road construction (NETL, 2010e)

The data used for these five processes are described below.

The natural gas conventional onshore well construction unit process was used as a proxy for geothermal well construction and installation. The unit process was modified to account for the difference in functional unit. The natural gas extraction model is based on 1 kg of natural gas output, whereas the geothermal power plant is based on 1 MWh of electricity. The inputs to this unit process are steel pipe and concrete (which are used as casing materials for the well) and diesel (which is combusted in drilling equipment during well installation). The energy and material flows for the upstream production and delivery of steel, concrete, and diesel are not included in this unit process but are accounted for by other unit processes. The output of this unit process is the fraction of the well materials and installation energy that is attributable to one MWh of geothermal produced electricity. This unit process also accounts for environmental emissions that are directly released by the combustion of diesel during well installation.

The balance of the geothermal power plant was modeled by using the natural gas combined cycle (NGCC) plant construction and installation unit process. Inputs to the unit process for the construction of the plant include steel plate, steel pipe, aluminum sheet, cast iron, and concrete. These inputs were scaled in the assembly based on the design capacity of the plant. The energy and material flows for the upstream production and delivery of steel, concrete, aluminum, cast iron are not included in this unit process but are accounted for by other unit processes. Diesel, water, and emissions associated with plant installation are also included and were also scaled based on the size of the plant. The process is based on the reference flow of 1 piece of geothermal power plant construction and installation per MWh of electricity produced. The NGCC construction unit process had a 50-mile trunkline already built into the model; however, in order to view the trunkline impacts separately and parameterize the distance, that trunkline was removed and replaced with the standalone unit process.

The pipeline used to transport fluid from the well to the balance of the geothermal plant was modeled using the natural gas pipeline construction/installation unit process. This process estimates the emissions consistent with welded steel pipeline manufacturing, installation and deinstallation. The process includes heavy construction equipment exhaust emissions, emissions from transport of pipes and associated materials (200 miles round-trip), and fugitive dust. The reference flow of this process is 1 mile of onshore pipeline (installed)

The trunkline unit process originally developed for modeling a 200 MW onshore wind farm was used as a proxy for the trunkline for the geothermal power plant. The unit process was modified to all for the parameterization of capacity factor, plant design net electricity output, and plant lifetime to reflect the difference between the geothermal plant and the wind farm. The trunkline distance was already parameterized in the unit process. This unit process provides a summary of relevant input and output flows associated with the construction of a trunkline that connects the geothermal power plant to the main electricity transmission grid. Key components include steel towers, concrete foundations, and steel-clad aluminum conductors. The lifetime electricity throughput of the trunkline is estimated in order to express the inputs and outputs on the basis of mass of materials per 1 MWh of electricity transport.

The access road unit process covers the materials required for the construction of a (linear) meter of gravel road, used onsite at a geothermal power plant, to facilitate the use of large/heavy transport trucks and other heavy duty vehicles for well installation and maintenance. The road is assumed to be constructed entirely of gravel. Installation of the road on site is presumed to require conventional diesel fuel for the use of grading and other construction equipment. The process is based on the reference flow of 1 meter of gravel road per MWh of electricity output from the geothermal power plant.

The modeling parameters used for geothermal power are shown in **Table B-1** and the inputs and outputs for the unit process are shown in **Table B-2**. **Table B-3** shows the construction material inputs for the geothermal facility by unit process.

Table B-1: Geothermal Power Modeling Parameters

Parameter	Expected Value	Units
Net Capacity	50	MW
Capacity Factor	90	%
Depth Per Well	10,600 (3,230)	ft. (m)
Number Of Production Wells	25	Count
Number Of Injection Wells	10	Count
Plant Life	25	Years
Trunkline Distance	25.0 (40.2)	Miles (km)

Table B-2: Unit Process Input and Output Flows

Flow Name	Value	Units (Per Reference Flow)
Inputs		
Trunkline Construction	1.015E-07	Pieces
Geothermal Well Construction and Installation	1.015E-07	Pieces
Plant Construction and Installation	1.015E-07	Pieces
Access Road Construction and Installation	1.015E-07	Pieces
Pipeline Construction and Installation	1.015E-07	Pieces
Outputs		
Electricity (Valuable Substance)	1	MWh
Carbon dioxide (Emissions to Air)	1.557E+00	kg
Methane (Emissions to Air)	1.498E-03	kg
Nitrous oxide (laughing gas) (Emissions to Air)	3.526E-05	kg
Nitrogen oxides (Emissions to Air)	1.180E-02	kg
Sulphur dioxide (Emissions to Air)	2.817E-03	kg
Carbon monoxide (Emissions to Air)	2.342E-02	kg
Dust (unspecified) (Emissions to Air)	1.560E-03	kg
Lead (+II) (Emissions to Air)	1.250E-06	kg
Mercury (+II) (Emissions to Air)	3.584E-08	kg
Ammonia (Emissions to Air)	1.703E-05	kg
Radioactive Emissions to Air	1.270E-08	kg
Group NMVOC to Air	2.962E-04	kg
Heavy Metals to Industrial Soil (Solid Waste)	6.730E-04	kg
Aluminum (+III) (Emissions to Water)	1.120E-06	kg
Ammonium / Ammonia (Emissions to Water)	1.795E-05	kg
Heavy Metals to Fresh Water (Emissions to Water)	3.189E-04	kg
Nitrate (Emissions to Water)	5.078E-06	kg
Nitrogen (Emissions to Water)	1.043E-06	kg
Phosphate (Emissions to Water)	2.930E-07	kg
Phosphorus (Emissions to Water)	4.837E-05	kg
Water (Emissions to Water)	4.760E+00	kg

Table B-3: Construction Material Flows by Unit Process

Unit Process	Material	Flow (kg/MWh)
Trunkline	Aluminum	2.35E-02
	Concrete	2.25E-01
	Steel cold rolled	1.31E-01
Well Construction and Installation	Steel, pipe welded	5.58E-02
	Concrete	5.58E-02
	Diesel	3.33E-01
Plant Construction and Installation	Aluminum	1.13E-03
	Concrete	3.47E-01
	Cast Iron	2.26E-03
	Steel, pipe welded	4.58E-02
	Steel plate	1.24E-01
Plant Installation	Diesel	1.13E-01
Access Road Construction and Installation	Diesel	2.32E-04
	Gravel	6.11E-01
Pipeline Construction and Installation	Diesel	1.62E-03
	Steel, pipe welded	7.37E-02

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Appendix C
Detailed Results Geothermal Power Modeling

List of Tables

Table C-1: Geothermal Detailed LCA Results

Category (Units)	Material or Energy Flow	ECF																PT	Total
					Plant Manufacturing									Well Construction					
		Access Road Construction	Operations	Pipeline	Aluminum Sheet	Cast Iron	Concrete	Electricity	Heavy Fuel Oil	Steel Pipe	Steel Plate	Plant Construction	Trunkline Construction	Concrete	Electricity	Steel Pipe	Well Installation	T&D	
GHG (kg/MWh)	CO_2	7.64E-04	2.30E+02	8.85E-02	1.28E-02	6.10E-02	4.80E-02	2.73E-03	1.20E-04	5.02E-02	1.43E-01	4.27E-01	5.60E-01	7.74E-03	9.67E-03	6.13E-02	2.19E-01	0.00E+00	2.31E+02
	N_2O	2.31E-07	0.00E+00	4.67E-06	2.22E-07	9.64E-07	0.00E+00	3.92E-08	1.05E-09	2.80E-06	7.44E-06	1.06E-05	7.56E-06	0.00E+00	1.53E-07	3.42E-06	0.00E+00	0.00E+00	3.81E-05
	CH_4	2.21E-06	4.27E-01	9.26E-05	2.11E-05	1.84E-04	0.00E+00	2.18E-06	1.24E-07	5.32E-05	1.09E-04	4.85E-04	7.95E-04	0.00E+00	2.92E-05	6.49E-05	1.20E-05	0.00E+00	4.29E-01
	SF_6	2.80E-16	0.00E+00	1.95E-15	1.30E-12	1.28E-08	0.00E+00	9.30E-15	5.15E-17	0.00E+00	0.00E+00	1.36E-13	8.25E-09	0.00E+00	2.04E-09	0.00E+00	0.00E+00	1.43E-04	1.43E-04
	CO_2e (IPCC 2007 100-yr GWP)	8.88E-04	2.40E+02	9.22E-02	1.34E-02	6.62E-02	4.80E-02	2.79E-03	1.23E-04	5.24E-02	1.48E-01	4.42E-01	5.83E-01	7.74E-03	1.05E-02	6.39E-02	2.19E-01	3.27E+00	2.45E+02
Other Air (kg/MWh)	Pb	3.35E-12	0.00E+00	2.47E-07	2.07E-09	4.04E-10	0.00E+00	1.36E-10	1.95E-11	1.53E-07	2.84E-07	1.64E-09	4.70E-07	0.00E+00	6.41E-11	1.87E-07	0.00E+00	0.00E+00	1.34E-06
	Hg	2.78E-13	0.00E+00	6.53E-09	1.67E-10	1.13E-09	0.00E+00	5.25E-12	9.01E-14	4.05E-09	1.78E-08	1.54E-10	3.58E-09	0.00E+00	1.79E-10	4.94E-09	0.00E+00	0.00E+00	3.86E-08
	NH_3	3.66E-07	4.53E-01	2.26E-07	4.79E-08	5.76E-08	0.00E+00	5.29E-09	6.97E-10	0.00E+00	0.00E+00	1.55E-05	1.92E-06	0.00E+00	9.14E-09	0.00E+00	0.00E+00	0.00E+00	4.53E-01
	CO	2.68E-05	0.00E+00	6.23E-04	1.11E-04	1.18E-05	6.19E-05	3.45E-06	4.41E-08	3.72E-04	1.21E-03	1.66E-02	4.63E-03	9.97E-06	1.87E-06	4.54E-04	1.04E-03	0.00E+00	2.52E-02
	NO_X	7.80E-05	0.00E+00	2.00E-04	2.25E-05	9.35E-05	1.47E-04	2.14E-06	1.37E-07	8.20E-05	2.40E-04	6.04E-03	9.52E-04	2.36E-05	1.48E-05	1.00E-04	4.53E-03	0.00E+00	1.25E-02
	SO_2	4.79E-07	0.00E+00	2.34E-04	7.10E-05	1.95E-04	1.12E-04	1.53E-06	5.06E-07	1.43E-04	3.26E-04	3.41E-04	1.46E-03	1.80E-05	3.10E-05	1.74E-04	0.00E+00	0.00E+00	3.11E-03
	VOC	2.27E-06	0.00E+00	2.91E-06	2.60E-06	1.65E-05	0.00E+00	7.13E-07	3.50E-08	-1.95E-13	-5.56E-13	2.03E-04	9.04E-05	0.00E+00	2.62E-06	-2.37E-13	1.21E-04	0.00E+00	4.43E-04
	PM	1.67E-04	0.00E+00	9.50E-05	2.18E-05	2.50E-06	1.43E-04	4.47E-06	2.23E-09	5.90E-05	3.43E-05	1.67E-06	6.93E-04	2.30E-05	3.96E-07	7.20E-05	0.00E+00	0.00E+00	1.32E-03
Solid Waste (kg/MWh)	Heavy Metals to Industrial Soil	9.05E-09	0.00E+00	6.32E-08	2.84E-07	4.02E-04	0.00E+00	1.26E-08	1.31E-09	0.00E+00	0.00E+00	4.42E-06	2.65E-04	0.00E+00	6.37E-05	0.00E+00	0.00E+00	0.00E+00	7.35E-04
	Heavy Metals to Agricultural Soil	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Water Use (L/MWh)	Withdrawal	5.49E-04	4.07E+01	9.12E-01	8.88E-02	2.12E+00	2.06E-02	6.77E-03	4.29E-05	5.64E-01	7.57E-01	1.25E+00	3.35E+00	3.32E-03	3.36E-01	6.88E-01	4.07E+00	0.00E+00	5.49E+01
	Discharge	1.34E-04	0.00E+00	9.32E-04	6.69E-02	1.96E+00	0.00E+00	2.60E-03	3.23E-05	0.00E+00	0.00E+00	6.52E-02	2.78E+00	0.00E+00	3.10E-01	0.00E+00	0.00E+00	0.00E+00	5.18E+00
	Consumption	4.16E-04	4.07E+01	9.12E-01	2.19E-02	1.63E-01	2.06E-02	4.18E-03	1.06E-05	5.64E-01	7.57E-01	1.18E+00	5.68E-01	3.32E-03	2.59E-02	6.88E-01	4.07E+00	0.00E+00	4.97E+01
Water Quality (kg/MWh)	Aluminum	0.00E+00	0.00E+00	0.00E+00	0.00E+00	8.66E-09	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	5.54E-09	0.00E+00	1.37E-09	0.00E+00	0.00E+00	0.00E+00	1.56E-08
	Arsenic (+V)	3.09E-09	0.00E+00	2.16E-08	4.09E-10	9.39E-08	0.00E+00	1.57E-11	2.88E-12	0.00E+00	0.00E+00	1.51E-06	7.06E-08	0.00E+00	1.49E-08	0.00E+00	0.00E+00	0.00E+00	1.71E-06
	Copper (+II)	4.53E-09	0.00E+00	3.16E-08	8.41E-10	1.12E-07	0.00E+00	3.18E-11	2.28E-11	0.00E+00	0.00E+00	2.21E-06	9.46E-08	0.00E+00	1.77E-08	0.00E+00	0.00E+00	0.00E+00	2.47E-06
	Iron	2.31E-07	0.00E+00	6.11E-06	2.87E-06	1.87E-06	0.00E+00	1.27E-07	1.79E-09	2.79E-06	4.63E-06	1.13E-04	6.75E-05	0.00E+00	2.97E-07	3.41E-06	0.00E+00	0.00E+00	2.03E-04
	Lead (+II)	1.04E-08	0.00E+00	1.01E-07	1.79E-09	4.58E-09	0.00E+00	4.76E-11	5.67E-12	1.76E-08	5.90E-08	5.08E-06	3.50E-08	0.00E+00	7.26E-10	2.15E-08	0.00E+00	0.00E+00	5.33E-06
	Manganese (+II)	1.39E-11	0.00E+00	9.68E-11	7.87E-09	1.44E-07	0.00E+00	7.01E-10	3.67E-12	0.00E+00	0.00E+00	6.77E-09	3.17E-07	0.00E+00	2.28E-08	0.00E+00	0.00E+00	0.00E+00	4.99E-07
	Nickel (+II)	8.24E-08	0.00E+00	5.83E-07	5.25E-10	4.29E-06	0.00E+00	6.65E-11	6.75E-12	5.15E-09	8.01E-09	4.02E-05	2.77E-06	0.00E+00	6.80E-07	6.28E-09	0.00E+00	0.00E+00	4.86E-05
	Strontium	7.59E-11	0.00E+00	5.30E-10	1.08E-08	3.12E-09	0.00E+00	2.79E-09	1.88E-10	0.00E+00	0.00E+00	3.70E-08	6.61E-07	0.00E+00	4.94E-10	0.00E+00	0.00E+00	0.00E+00	7.16E-07
	Zinc (+II)	1.43E-07	0.00E+00	1.01E-06	6.58E-10	1.19E-06	0.00E+00	6.94E-11	5.79E-12	5.56E-09	3.53E-08	6.98E-05	7.87E-07	0.00E+00	1.89E-07	6.78E-09	0.00E+00	0.00E+00	7.32E-05
	NH_3	1.17E-06	0.00E+00	8.71E-06	4.77E-08	1.05E-05	0.00E+00	7.65E-09	1.56E-10	3.23E-07	4.50E-06	5.73E-04	8.06E-06	0.00E+00	1.66E-06	3.94E-07	0.00E+00	0.00E+00	6.08E-04
	HCl	2.91E-14	0.00E+00	2.03E-13	8.06E-13	7.31E-13	0.00E+00	1.17E-14	4.41E-15	0.00E+00	0.00E+00	1.42E-11	1.89E-11	0.00E+00	1.16E-13	0.00E+00	0.00E+00	0.00E+00	3.50E-11
	Nitrogen (as total N)	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.03E-08	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.94E-08	0.00E+00	4.80E-09	0.00E+00	0.00E+00	0.00E+00	5.45E-08
	Phosphate	3.43E-12	0.00E+00	2.40E-11	2.65E-09	3.57E-10	0.00E+00	4.49E-11	1.99E-11	0.00E+00	0.00E+00	1.68E-09	3.11E-07	0.00E+00	5.66E-11	0.00E+00	0.00E+00	0.00E+00	3.16E-07
	Phosphorus	1.04E-07	0.00E+00	7.27E-07	4.69E-10	6.75E-08	0.00E+00	1.61E-11	3.42E-12	2.90E-09	4.82E-07	5.05E-05	5.50E-08	3.48E-03	0.00E+00	0.00E+00	1.04E-01	0.00E+00	1.07E-01
Resource Energy (MJ/MWh)	Crude Oil	9.44E-03	0.00E+00	2.03E-01	2.19E-02	4.66E-02	0.00E+00	0.00E+00	1.33E-03	8.50E-02	3.14E-01	4.61E+00	1.18E+00	3.48E-03	0.00E+00	0.00E+00	1.04E-01	0.00E+00	6.58E+00
	Hard Coal	1.39E-04	0.00E+00	5.69E-01	1.93E-01	4.37E-02	0.00E+00	0.00E+00	1.89E-05	3.52E-01	1.37E+00	8.23E-02	3.28E+00	3.06E-02	0.00E+00	0.00E+00	4.30E-01	0.00E+00	6.35E+00
	Lignite	5.08E-06	0.00E+00	3.54E-05	1.02E-04	1.49E-02	0.00E+00	0.00E+00	1.52E-06	0.00E+00	0.00E+00	3.23E-03	3.92E-01	1.61E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00	4.11E-01
	Natural Gas	1.06E-03	0.00E+00	2.42E-01	2.73E-01	3.53E-02	0.00E+00	0.00E+00	1.78E-04	1.45E-01	2.73E-01	5.20E-01	1.34E+00	4.33E-02	0.00E+00	0.00E+00	1.77E-01	0.00E+00	3.05E+00
	Uranium	6.75E-05	0.00E+00	4.71E-04	3.72E-04	4.83E-02	0.00E+00	0.00E+00	9.47E-06	0.00E+00	0.00E+00	3.42E-02	8.16E-01	5.90E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00	9.00E-01
	Total Resource Energy	1.07E-02	0.00E+00	1.01E+00	4.88E-01	1.89E-01	0.00E+00	0.00E+00	1.53E-03	5.83E-01	1.96E+00	5.25E+00	7.00E+00	7.74E-02	0.00E+00	0.00E+00	7.11E-01	0.00E+00	1.73E+01
Energy Return on Investment		N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	208:1

Table C-2: Geothermal Detailed LCA Results in Alternate Units

Category (Units)	Material or Energy Flow	ECF																PT	Total
					Plant Manufacturing									Well Construction					
		Access Road Construction	Operations	Pipeline	Aluminum Sheet	Cast Iron	Concrete	Electricity	Heavy Fuel Oil	Steel Pipe	Steel Plate	Plant Construction	Trunkline Construction	Concrete	Electricity	Steel Pipe	Well Installation	T&D	
GHG (lb/MWh)	CO_2	1.68E-03	5.06E+02	1.95E-01	2.83E-02	1.34E-01	1.06E-01	6.01E-03	2.64E-04	1.11E-01	3.16E-01	9.41E-01	1.24E+00	1.71E-02	2.13E-02	1.35E-01	4.83E-01	0.00E+00	5.10E+02
	N_2O	5.08E-07	0.00E+00	1.03E-05	4.90E-07	2.12E-06	0.00E+00	8.64E-08	2.31E-09	6.18E-06	1.64E-05	2.33E-05	1.67E-05	0.00E+00	3.37E-07	7.54E-06	0.00E+00	0.00E+00	8.39E-05
	CH_4	4.88E-06	9.41E-01	2.04E-04	4.65E-05	4.07E-04	0.00E+00	4.80E-06	2.72E-07	1.17E-04	2.40E-04	1.07E-03	1.75E-03	0.00E+00	6.45E-05	1.43E-04	2.64E-05	0.00E+00	9.45E-01
	SF_6	6.16E-16	0.00E+00	4.30E-15	2.87E-12	2.83E-08	0.00E+00	2.05E-14	1.14E-16	0.00E+00	0.00E+00	3.01E-13	1.82E-08	0.00E+00	4.49E-09	0.00E+00	0.00E+00	3.16E-04	3.16E-04
	CO_2e (IPCC 2007 100-yr GWP)	1.96E-03	5.30E+02	2.03E-01	2.96E-02	1.46E-01	1.06E-01	6.16E-03	2.72E-04	1.16E-01	3.27E-01	9.74E-01	1.28E+00	1.71E-02	2.31E-02	1.41E-01	4.83E-01	7.20E+00	5.41E+02
Other Air (lb/MWh)	Pb	7.39E-12	0.00E+00	5.44E-07	4.55E-09	8.91E-10	0.00E+00	2.99E-10	4.29E-11	3.37E-07	6.26E-07	3.61E-09	1.04E-06	0.00E+00	1.41E-10	4.12E-07	0.00E+00	0.00E+00	2.96E-06
	Hg	6.14E-13	0.00E+00	1.44E-08	3.68E-10	2.49E-09	0.00E+00	1.16E-11	1.99E-13	8.93E-09	3.93E-08	3.39E-10	7.90E-09	0.00E+00	3.95E-10	1.09E-08	0.00E+00	0.00E+00	8.50E-08
	NH_3	8.08E-07	1.00E+00	4.98E-07	1.06E-07	1.27E-07	0.00E+00	1.17E-08	1.54E-09	0.00E+00	0.00E+00	3.43E-05	4.23E-06	0.00E+00	2.01E-08	0.00E+00	0.00E+00	0.00E+00	1.00E+00
	CO	5.91E-05	0.00E+00	1.37E-03	2.44E-04	2.61E-05	1.36E-04	7.62E-06	9.72E-08	8.20E-04	2.66E-03	3.66E-02	1.02E-02	2.20E-05	4.13E-06	1.00E-03	2.29E-03	0.00E+00	5.55E-02
	NO_X	1.72E-04	0.00E+00	4.42E-04	4.97E-05	2.06E-04	3.23E-04	4.72E-06	3.01E-07	1.81E-04	5.29E-04	1.33E-02	2.10E-03	5.20E-05	3.27E-05	2.20E-04	9.99E-03	0.00E+00	2.76E-02
	SO_2	1.06E-06	0.00E+00	5.17E-04	1.57E-04	4.30E-04	2.46E-04	3.38E-06	1.12E-06	3.15E-04	7.19E-04	7.52E-04	3.22E-03	3.97E-05	6.82E-05	3.84E-04	0.00E+00	0.00E+00	6.86E-03
	VOC	5.01E-06	0.00E+00	6.41E-06	5.74E-06	3.64E-05	0.00E+00	1.57E-06	7.71E-08	-4.29E-13	-1.22E-12	4.48E-04	1.99E-04	0.00E+00	5.78E-06	-5.23E-13	2.67E-04	0.00E+00	9.76E-04
	PM	3.68E-04	0.00E+00	2.10E-04	4.80E-05	5.51E-06	3.15E-04	9.85E-06	4.93E-09	1.30E-04	7.57E-05	3.68E-06	1.53E-03	5.08E-05	8.74E-07	1.59E-04	0.00E+00	0.00E+00	2.90E-03
Solid Waste (lb/MWh)	Heavy Metals to Industrial Soil	2.00E-08	0.00E+00	1.39E-07	6.27E-07	8.86E-04	0.00E+00	2.78E-08	2.90E-09	0.00E+00	0.00E+00	9.75E-06	5.83E-04	0.00E+00	1.40E-04	0.00E+00	0.00E+00	0.00E+00	1.62E-03
	Heavy Metals to Agricultural Soil	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Water Use (gal/MWh)	Withdrawal	1.45E-04	1.08E+01	2.41E-01	2.35E-02	5.60E-01	5.44E-03	1.79E-03	1.13E-05	1.49E-01	2.00E-01	3.29E-01	8.84E-01	8.76E-04	8.87E-02	1.82E-01	1.08E+00	0.00E+00	1.45E+01
	Discharge	3.53E-05	0.00E+00	2.46E-04	1.77E-02	5.17E-01	0.00E+00	6.86E-04	8.54E-06	0.00E+00	0.00E+00	1.72E-02	7.34E-01	0.00E+00	8.19E-02	0.00E+00	0.00E+00	0.00E+00	1.37E+00
	Consumption	1.10E-04	1.08E+01	2.41E-01	5.79E-03	4.31E-02	5.44E-03	1.10E-03	2.79E-06	1.49E-01	2.00E-01	3.12E-01	1.50E-01	8.76E-04	6.84E-03	1.82E-01	1.08E+00	0.00E+00	1.31E+01
Water Quality (lb/MWh)	Aluminum	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.91E-08	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.22E-08	0.00E+00	3.03E-09	0.00E+00	0.00E+00	0.00E+00	3.43E-08
	Arsenic (+V)	6.81E-09	0.00E+00	4.76E-08	9.02E-10	2.07E-07	0.00E+00	3.47E-11	6.36E-12	0.00E+00	0.00E+00	3.33E-06	1.56E-07	0.00E+00	3.28E-08	0.00E+00	0.00E+00	0.00E+00	3.78E-06
	Copper (+II)	9.98E-09	0.00E+00	6.97E-08	1.85E-09	2.46E-07	0.00E+00	7.01E-11	5.02E-11	0.00E+00	0.00E+00	4.87E-06	2.09E-07	0.00E+00	3.91E-08	0.00E+00	0.00E+00	0.00E+00	5.45E-06
	Iron	5.09E-07	0.00E+00	1.35E-05	6.33E-06	4.13E-06	0.00E+00	2.80E-07	3.95E-09	6.16E-06	1.02E-05	2.49E-04	1.49E-04	0.00E+00	6.55E-07	7.51E-06	0.00E+00	0.00E+00	4.46E-04
	Lead (+II)	2.29E-08	0.00E+00	2.23E-07	3.94E-09	1.01E-08	0.00E+00	1.05E-10	1.25E-11	3.89E-08	1.30E-07	1.12E-05	7.71E-08	0.00E+00	1.60E-09	4.74E-08	0.00E+00	0.00E+00	1.18E-05
	Manganese (+II)	3.06E-11	0.00E+00	2.13E-10	1.74E-08	3.17E-07	0.00E+00	1.55E-09	8.09E-12	0.00E+00	0.00E+00	1.49E-08	6.98E-07	0.00E+00	5.03E-08	0.00E+00	0.00E+00	0.00E+00	1.10E-06
	Nickel (+II)	1.82E-07	0.00E+00	1.29E-06	1.16E-09	9.45E-06	0.00E+00	1.47E-10	1.49E-11	1.13E-08	1.76E-08	8.86E-05	6.10E-06	0.00E+00	1.50E-06	1.38E-08	0.00E+00	0.00E+00	1.07E-04
	Strontium	1.67E-10	0.00E+00	1.17E-09	2.38E-08	6.87E-09	0.00E+00	6.16E-09	4.16E-10	0.00E+00	0.00E+00	8.17E-08	1.46E-06	0.00E+00	1.09E-09	0.00E+00	0.00E+00	0.00E+00	1.58E-06
	Zinc (+II)	3.15E-07	0.00E+00	2.22E-06	1.45E-09	2.63E-06	0.00E+00	1.53E-10	1.28E-11	1.22E-08	7.77E-08	1.54E-04	1.73E-06	0.00E+00	4.17E-07	1.49E-08	0.00E+00	0.00E+00	1.61E-04
	NH_3	2.59E-06	0.00E+00	1.92E-05	1.05E-07	2.31E-05	0.00E+00	1.69E-08	3.44E-10	7.11E-07	9.92E-06	1.26E-03	1.78E-05	0.00E+00	3.67E-06	8.68E-07	0.00E+00	0.00E+00	1.34E-03
	HCl	6.41E-14	0.00E+00	4.48E-13	1.78E-12	1.61E-12	0.00E+00	2.58E-14	9.72E-15	0.00E+00	0.00E+00	3.13E-11	4.16E-11	0.00E+00	2.56E-13	0.00E+00	0.00E+00	0.00E+00	7.71E-11
	Nitrogen (as total N)	0.00E+00	0.00E+00	0.00E+00	0.00E+00	6.68E-08	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	4.27E-08	0.00E+00	1.06E-08	0.00E+00	0.00E+00	0.00E+00	1.20E-07
	Phosphate	7.57E-12	0.00E+00	5.28E-11	5.83E-09	7.87E-10	0.00E+00	9.89E-11	4.39E-11	0.00E+00	0.00E+00	3.70E-09	6.85E-07	0.00E+00	1.25E-10	0.00E+00	0.00E+00	0.00E+00	6.96E-07
	Phosphorus	2.28E-07	0.00E+00	1.60E-06	1.03E-09	1.49E-07	0.00E+00	3.54E-11	7.55E-12	6.40E-09	1.06E-06	1.11E-04	1.21E-07	7.67E-03	0.00E+00	0.00E+00	2.29E-01	0.00E+00	2.36E-01
Resource Energy (Btu/MWh)	Crude Oil	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Hard Coal	1.31E-01	0.00E+00	5.39E+02	1.83E+02	4.14E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.11E+03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.87E+03
	Lignite	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Natural Gas	1.01E+00	0.00E+00	2.29E+02	2.59E+02	3.35E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.27E+03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.79E+03
	Uranium	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Total Resource Energy	1.02E+01	0.00E+00	9.61E+02	4.63E+02	1.79E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	6.64E+03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	8.25E+03
Energy Return on Investment		N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	208:1