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LIFE CYCLE ENVIRONMENTAL IMPACTS OF GEOTHERMAL SYSTEMS

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ABSTRACT

Geothermal energy is increasingly recognized for its potential to reduce greenhouse gas emissions. Studies have shown that air emissions, water consumption, and land use under geothermal electricity generation will have less of an environmental impact than traditional fossil fuel-based electricity generators. However, the environmental impacts of geothermal energy across its life cycle, including the construction of well fields and production facilities, are less well understood.

With a potential threefold increase in geothermal electricity generation by 2035, the lifecycle impacts of geothermal technologies must be explored. This paper presents potential impacts and factors associated with construction, drilling, and production activities of enhanced geothermal systems (EGS), hydrothermal binary, hydrothermal flash, and geopressured geothermal systems. Five power plant scenarios were evaluated: a 20-MW EGS plant, a 50-MW EGS plant, a 10-MW binary plant, a 50-MW flash plant, and a 3.6-MW geopressured plant that coproduces natural gas. The impacts associated with these power plant scenarios are compared with those from other electricity generating technologies.

INTRODUCTION

The Energy Information Administration of the U.S. Department of Energy projects that renewable electricity, which now represents around 12.8% of U.S. electricity generation, will increase to 15–20% by 2035 (USDOE 2011a). While most of the increase in renewable electricity is projected to come from wind turbines and biomass combustion plants, geothermal electricity generation is projected to increase threefold (USDOE 2011a). Geothermal power, customarily associated with states with conspicuous geothermal resources, could grow even more if enhanced geothermal systems (EGS) and low-temperature resources prove to be cost effective and environmentally benign. Geothermal power could become a viable option for many states and in the process become a significant contributor to the U.S. power infrastructure.

With significant potential growth opportunities for geothermal technologies, it is important to understand their material, energy, and water requirements and potential environmental impacts. Argonne National Laboratory conducted lifecycle analyses to evaluate these requirements and impacts associated with EGS, hydrothermal flash, hydrothermal binary, and geopressured power-generating technologies. Argonne's Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model was expanded to address lifecycle emissions and energy issues so that comparisons in fossil energy use, petroleum use, greenhouse gas emissions, and criteria air pollutant emissions by geothermal technologies could be thoroughly examined by stakeholders. The results of the analyses are summarized here and are presented in detail in Sullivan et al. (2010) and Clark et al. (2011), with the exception of geopressured geothermal systems.

METHODOLOGY

To evaluate the technologies, a process-based life cycle analysis was conducted considering activities associated with drilling, stimulation, construction, and operating the wells and the power plant. Scenarios were developed for each technology. The methodology is summarized below. A detailed methodology is presented in Sullivan et al. (2010).

Scenario Development

Five scenarios were developed with input from experts in industry and other national laboratories. Detailed assumptions for the scenarios are listed in

Table 1: Parameters evaluated for the various geothermal technology scenarios.

Parameters	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Geothermal Technology	EGS	EGS	hydrothermal	hydrothermal	geopressured
Net Power Output, MW	20	50	10	50	
Producer-to-Injector Ratio	2:1	2:1	3:1 and 2:1	3:1 and 2:1	2:1
Number of Turbines	single	multiple	single	multiple	single
Generator Type	binary	binary	binary	flash	binary
Cooling	air	air	air	evaporative	air
Temperature, ^{o}C	150–225	150–225	150–185	175–300	130–150
Thermal Drawdown, % per year	0.3	0.3	0.4–0.5	0.4–0.5	0
Well Replacement	1	1	1	1	0
Exploration Wells	1	1 or 2	1	1	0
Well Depth, km	4–6	4–6	<2	1.5, <3	4–6 (producers) 2–3 (injectors)
Flow Rate per Well, kg/s	30–90	30–90	60–120	40–100	35–55
Gas/Brine Ratio, scf/stb	not applicable	not applicable	not applicable	not applicable	25–35
Pumps for Production	submersible 10,000 ft	submersible 10,000 ft	lineshaft or submersible	none	none
Distance between Wells, m	600–1,000	600–1,000	800–1,600	800–1,600	1,000
Location of Plant in Relation to Wells	central	central	central	central	central
Plant Lifetime, years	30	30	30	30	30

Table 1. The scenarios were modeled in the U.S. Department of Energy's Geothermal Electricity Technology Evaluation Model (GETEM), and the simulation was run multiple times in GETEM to create a range of possible outcomes (USDOE 2011b).

Drilling, Stimulation and Construction Stage

For the EGS binary 1 and 2 scenarios, well designs were based on the 5,000-m EGS wells described in *The Future of Geothermal Energy* (Tester et al., 2006). The binary and flash hydrothermal systems were based on the design configuration of well RRGE2 in Raft River, Idaho (Narasimhan and Witherspoon, 1977). For the geopressured scenario, the well designs were based on the reworked wells at Pleasant Bayou (Randolph et al., 1992). All designs were modified to assess material requirements for wells at various depths (Sullivan et al., 2010). The designs were used to determine the amount of materials, water, and fuel required in the drilling, casing, and cementing of a well.

To determine the amount of drilling fluid required, water and mud materials were estimated. A ratio of 1 bbl of water to 1 bbl of drilling mud and a ratio of 5 bbl mud to 1 bbl void space were assumed (USEPA, 1993). The composition of the mud was provided by ChemTech Services as summarized by Mansure (2010) to provide the required drilling fluid properties. Because the dominant material by several orders of magnitude was bentonite, the other materials were ignored for this study.

Stimulation was considered for the two EGS scenarios. Published information on EGS stimulation projects and the volumes of fluids used is limited, and available literature values are from international projects with different geological characteristics than potential projects in the United States. The average volume from literature values was found to be 26,939 m^3 (169,440 bbl) of water per well (Asanuma et al., 2004; Michelet and Toksöz, 2006; Zimmermann et al., 2009; Tester et al., 2006).

For power plant construction, two designs (flash and binary) were evaluated using the "Investigation of Cost and Reliability in Utility Systems" model Investigation of Cost and Reliability in Utility Systems (ICARUS) Process Evaluator. This evaluator enables estimating of costs, components, and material requirements for building new production facilities. A typical ICARUS output includes the following items: lengths of pipes of various diameters and wall thicknesses, lengths of wire of various load capacities, numbers of valves of different sizes, required pieces of equipment and their weights, amounts of reinforcing bar (rebar), paint, insulation, concrete, cement, and numerous other components. For equipment, constituent types of steel were also given. Lengths of pipe and wire were readily converted to masses of steel and copper used in the plant associated with those parts. Because steel, cement, concrete, and aluminum make up the bulk of the plant mass, we focused primarily on these materials for our weight estimates.

Operations Stage

During operations, the primary concern for geothermal plants from a lifecycle perspective is water use. The vast majority of water used during operations is used to generate electricity. This water, which is extracted from the resource, is commonly referred to as the geofluid. In binary systems, the geofluid is reinjected into the reservoir. In a flash system, geofluid that is flashed to vapor is released to the atmosphere while the condensed geofluid is returned to the reservoir. In addition to geofluid for electricity generation, freshwater may be used to condense vapor for (1) reinjection in the case of the geofluid, (2) reuse in the case of the working fluid in binary systems, and (3) maintenance of reservoir pressure for long-term sustainability. Reservoir loss for EGS is currently being investigated by Argonne National Laboratory and is not presented here. Freshwater may also be used in normal geothermal power plant operations to manage dissolved solids and minimize scaling. For the geopressured geothermal power plant evaluated in this study, the spent geofluid is directed to a separate disposal well that does not maintain reservoir pressure. Freshwater consumption for the geopressured scenario should be minimal in this phase.

The total flow rate of geofluid through the plant depends on the flow rate produced from each well and the total number of production wells. Table 2 presents typical flow rates for various geothermal technologies. The lower temperature systems (i.e., binary and geopressured) typically have higher production volumes per MWe than the higher temperature systems (i.e., flash and EGS).

In addition to the water use that occurs for all geothermal technologies evaluated, hydrothermal flash systems and geopressured geothermal systems have additional environmental burdens during operations. For hydrothermal flash systems, the geofluid that is flashed releases significant dissolved gases, including greenhouse gases (GHGs), into the atmosphere. Bloomfield et al. (2003) reported a weighted average emissions output of 91 g/kWh from U.S. geothermal power plants. Their average includes the zero GHG emissions from binary plants, which represent 14% of the surveyed capacity. When adjusted for flash plants only, the average becomes 106 g/kWh. Unfortunately, no mention of the range of U.S. geothermal emissions rates was given by Bloomfield et al. (2003). Their results are based on a study wherein individual sources and values for provided emission rates remain confidential.

Table 2: Typical flow rates for various geothermal technologies.

Geothermal Technology	Daily Flow Rate (kg/day/MWe)
EGS[a]	1,242,000–1,627,000
Binary[b]	1,488,000–1,939,000
Flash[b]	353,000–648,000
Geopressured	2,160,000–2,210,000

[a] Flow rates from Sullivan et al. (2010) and Clark et al. (2011).

[b] Flow rates based on annual production data (CDOGGR, 2009).

Another method used to estimate the GHG distribution from U.S. geothermal plants employed emissions data reported from the California Environmental Protection Agency (CEPA, 2008). However, these data are exclusively from California facilities and as such may not be very representative of the U.S. geothermal plants as a whole. The California geothermal emissions arise from about 1,800 MW of capacity and have a weighted average emission rate of 68 g/kWh.

For geopressured systems, GHG emissions arise from both natural gas production and use. The emissions vary according to the gas:brine ratio shown in Table 1 and according to whether the natural gas is delivered to a pipeline or combusted onsite for electricity generation. The emissions associated with the natural gas production, processing, transportation or combustion are based on Argonne's GREET model (GREET 1.8 data for fuel production and use), and the plant-cycle CO_2 is based on work by Burnham et al. (2011).

RESULTS OF THE LIFECYCLE ANALYSIS

Pathways for the various geothermal technologies were developed using the GREET model according to the assumptions described in the methodology and compared to other electricity generating technologies. The results of the analysis are discussed below.

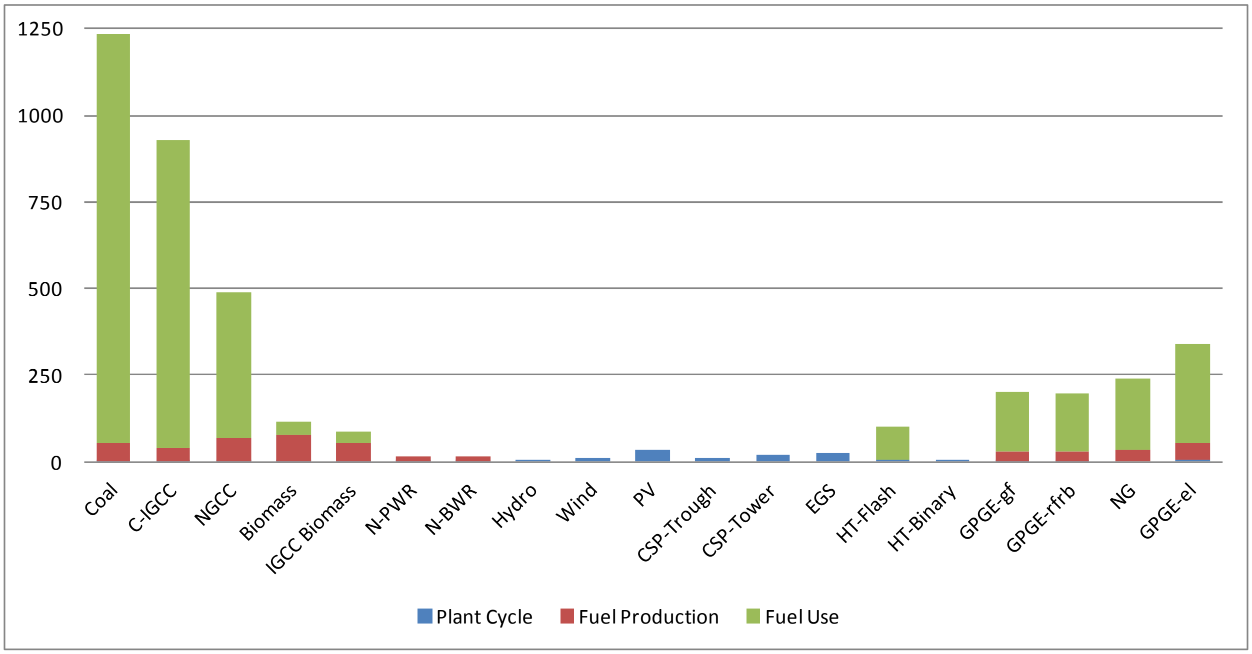

Figure 1: Greenhouse gas emissions (g/kWh) by lifecycle stage for various power production technologies relative to total energy output; entries based on average MPRs given above and GREET 1.8 data.

Greenhouse Gas Emissions

Figure 1 summarizes our lifecycle GHG emissions estimates (grams per kWh) by lifecycle stage for the various power technologies considered. Fossil-fuel plants generate much more GHGs per kWh than renewable, hybrid, and nuclear power plants. For the fossil electricity plants, the preponderance of GHGs per kWh arises from the fuel burned to produce the electricity.

It also is clear from the figure that all plants have some GHG emissions in their life cycles. For example, GHG emissions are emitted during nuclear fuel production as a result of fuel use during uranium mining and processing. The GHGs associated with hydropower, wind, photovoltaic (PV) power, combined solar power (CSP), and EGS are all quite small and arise from the plant cycle stage.

Of the renewable and hybrid technologies, hydropower, wind, PV power, CSP, EGS, and hydrothermal binary (HT-Binary) are the lowest GHG emitters of the technologies covered. On the other hand, geopressured geothermal energy (GPGE), hydrothermal flash (HT-Flash), and biomass power have the highest GHG emissions for these technologies, although as seen in Figure 1 they are considerably less than those from fossil-fuel-based power plants. For hydrothermal flash, the GHGs are fuel use emissions and come primarily from dissolved CO_2 in the geofluid that is released to the atmosphere upon its passage through the plant.

Hydrothermal flash emissions are similar to biomass-based power, whether from conventional boiler or IGCC facility. Most of the GHGs are from the fuel production stage, when fuel is used for harvesting forestry residues.

As a hybrid technology, geopressured systems have, as expected, a higher GHG emission rate than those for the renewables, although these rates are again small in comparison to those from strictly fossil-based power production. Geopressured system emissions arise from both natural gas production and use. For comparison purposes, a natural gas (NG) bar has been added to Figure 1, representing the production of solely natural gas from wells associated with the geopressured system. When this bar is compared to those for the geopressured dual-output systems, it is conspicuously higher because its lacks the leveraging effect of the dual-output GPGE plants.

Not discussed here but described in the methodology in Sullivan et al. (2011) is that despite infrastructure requirement differences between greenfield wells for geopressured systems (GPGE-gf) and refurbished wells for geopressured systems (GPGE-rfrb) there is an insignificant difference in lifecycle GHGs. This is because plant cycle emission is very small in comparison to energy production and use emissions.

The GHG emissions for geopressured with natural gas onsite electricity generation (GPGE-el) are roughly two-thirds of those from the conventional NGCC facility at the left of the figure. When compared to just delivering a thermal MW of produced natural gas, the extra gas needed to produce a MW of electricity is offset in part by the extra electric power derived from the hot geofluid. The GPGE-el GHG emissions are about 50% higher than those for GPGE-gf and GPGE-rfrb. This is because of the greater energy output from the dual-output plants compared to the all-electric-output GPGE. Because plant output is defined as both gas and electric energy delivered to the consumer, gas delivered to a pipeline provides greater energy leverage, even if the customer later uses the gas from the pipeline to generate electricity. In that case, the burden belongs to the customer and not the geopressured power plant.

Water Consumption

Table 3 summarizes by lifecycle stage our water consumption estimates (gallons per kWh) for the various power technologies considered. The water consumption estimates for non-geothermal technologies are values presented in the literature and may not consider all lifecycle stages.

For the geothermal scenarios, the water consumption for the EGS construction stage is much greater than the other geothermal scenarios. This is primarily due to the additional requirement of reservoir stimulation for EGS. No stimulation was assumed for the other scenarios. Stimulation volume is assumed to be dependent on the desired water volume flow rate (a function of plant capacity) and to be independent of depth. The water volume required for stimulation contributes approximately 60–80% of total upfront water requirements for the evaluated well depths. Water requirements for stimulation can vary from the estimate presented here according to (1) the number of stimulations required for successful circulation and (2) the reuse of water for multiple stimulations.

When water consumption is normalized across the life cycle, the contribution of stimulation is small, and the vast majority of water consumption for all geothermal technologies with the exception of geopressured systems occurs during the operations phase.

According to Table 3, wind, hydrothermal (geothermal) flash, and geopressured systems consume the least amount of

Table 3: Aggregated Water Consumption for Electric Power Generation at Indicated Life Cycle Stages in Gallons per kWh of Lifetime Energy Output.[a]

Power Plant	Fuel Production	Plant Construction	Plant Operations	Total Life Cycle[b]
Coal	0.26	–	0.004–1.2	0.26–1.46
Coal with carbon capture	0.01–0.17	0.13–0.25	0.5–1.2	0.57–1.53
Nuclear	0.14	–	0.14–0.85	0.28–0.99
Natural gas conventional	0.29	–	0.09–0.69	0.38–0.98
Natural gas combined cycle	0.22	–	0.02–0.5	0.24–0.72
Hydroelectric (dam)	–	–	4.5	4.5
Concentrated solar power	–	0.02–0.08	0.77–0.92	0.87–1.12
Solar photovoltaic	–	0.06–0.15	0.006–0.02	0.07–0.19
Wind (onshore)[c]	–	0.02	3.62E-08	0.01
Geothermal EGS	–	0.01	0.29–0.72	0.3–0.73
Geothermal binary[d]	–	0.001	0.08–0.27	0.08–0.271
Geothermal flash[d]	–	0.001	0.005–0.01	0.01
Geothermal geopressured	–	4E-04–5E-04	–	4E-04–5E-04
Biomass	–	–	0.3–0.61	0.3–0.61

[a] Sources: Adee and Moore (2010); Frick et al. (2010); Gleick (1994); Goldstein and Smith (2002); Harto et al. (2010); Maulbetsch and DiFilippo (2006); NETL (2005, 2007, 2008); Vestas Wind Systems A/S (2006).

[b] Reported when provided, otherwise summed from values in table.

[c] Assumes recovery of water in the end-of-life management stage.

[d] Assumes water consumed as makeup for operational loss is a small percentage of total operational geofluid loss.

water across the life cycle of the electricity generation technologies considered. For the geothermal technologies, this is based on several assumptions. Water cooling towers are typically used for flash plants, because these plants provide much of the needed water from steam condensate (DiPippo, 2008). The flash power plant in our scenario assumes that the cooling tower relies on the steam condensate generated after the geofluid is flashed. According to GETEM, the single-stage flash power plant modeled would lose an average 2.7 gal/kWh of geofluid from the reservoir due to evaporation, drift, and blowdown. Reliance on the geofluid for cooling reduces the freshwater makeup requirements for operations. However, the geofluid loss over the lifetime may decrease the sustainability of the reservoir.

As previously discussed, for geopressured systems, the spent geofluid is typically directed to a disposal well that is not connected to the geopressured reservoir. Because of this, freshwater is not used during operations as makeup water. For air-cooled geopressured systems, this results in negligible freshwater consumption during operations.

The binary and EGS scenarios also assumed air cooling. Water consumption was based on historical data for binary plants provided by the California Division of Oil, Gas, and Geothermal Resources (CDOGGR, 2009). Available production and injection data were analyzed to determine typical makeup and loss rates. This resulted in operational water consumption estimates of 0.27 gal/kWh for binary systems and 0.29–0.72 gal/kWh for EGS. The range for EGS depends upon the extent to which geofluid loss during operations would need to be replaced with freshwater to maintain reservoir pressure. This typical operational makeup water volume is based on an operating air-cooled binary plant. Typical operations and maintenance activities including maintenance of reservoir pressure or switching to evaporative cooling during summer daytime operations may be responsible for makeup volume requirements.

These binary and EGS estimates are greater than those reported by Frick et al. (2010) for EGS. Frick et al. (2010) conducted a life cycle analysis (LCA) on enhanced low-temperature binary systems that rely on wet cooling and found operational water consumption to be 0.08 gal/kWh assuming an average conversion efficiency of 10.5%. However, for the overall life cycle, the consumption for EGS power plants for this study is similar to data provided by Frick et al. (2010), who provided component estimates of consumption that aggregate to 0.36 gal/kWh over the lifetime energy output. Frick et al. (2010) identifies the construction stage, particularly well stimulation referred to as "reservoir enhancement," as the stage primarily responsible for water consumption requirements. If reservoir enhancement includes makeup water to address declining geofluid water volumes over time, some of the volume may be accounted for in the makeup water requirements identified in the operations stage of the EGS power plant life cycles presented here.

Reported literature values typically focus on the operational stage of electrical power plant life cycles. Other stages may be important depending upon the technology. Two such stages include the construction stage for geothermal plants and the fuel production stage for fuel-based electricity-generating plants such as biomass, coal, natural gas, and nuclear plants.

With the exception of coal with carbon capture, all electric-generating technologies in Table 3 are reported in the literature to consume less than 1 gal of water per kilowatt hour of lifetime energy output on average. Average values of consumption for coal, nuclear, and conventional natural gas power plant systems are higher than for geothermal scenarios. However, because consumption depends on cooling technology, it is not surprising that reported low consumption values for thermoelectric technologies including coal, nuclear, conventional natural gas, NGCC, EGS, and biomass are similarly near 0.3 gal/kWh. Geothermal flash, geopressured systems, and wind appear to be more water efficient. Overall, the geothermal technologies considered in this study appear to consume less water on average over the lifetime energy output than other power generation technologies.

SUMMARY AND IMPLICATIONS

This report presents a comprehensive and comparative LCA of GHG emissions and water consumption for large-scale geothermal power plant systems. Total GHG emissions are by far the largest for fossil power plants and are much lower for renewable power systems. GHG emissions that exist for renewable systems tend to be dominated by plant construction; however, flash and geopressured geothermal emissions are primarily attributable to GHGs emitted during the plant operation stage of the life cycle and GHG emissions for biomass plants are dominated by the fuel production lifecycle stage. Despite the large amounts of steel and concrete required per MW power capacity, enhanced geothermal systems are one of the lower GHG emitters of the renewable systems studied in terms of lifetime kWh output. EGS GHG emissions can be reduced even further as well depth decreases.

Geothermal power plants consume less water per kilowatt-hour of lifetime energy output compared to other electric power generation technologies. Of the geothermal technologies, geopressured and flash power plants consume the least water. For flash power plants, the low consumption is due to their reliance on geofluid for cooling, although the long-term sustainability of such an approach is unknown with average geofluid losses estimated at 2.7 gal/kWh. For geopressured systems, management of produced geofluid is a greater concern than water consumption, similar to conventional gas production. For binary systems, only wind and PV electric power systems reportedly consume less water. EGS power plants have similar water consumption rates to NGCC and biomass power plants, although the water use for biomass power plants is likely to be higher than estimated because fuel production water requirements were not included in our analysis.

For all geothermal systems evaluated, with the exception of geopressured systems, the operational makeup water requirement was found to be the largest consumer of water. The operation water losses for the binary and EGS scenarios were based on available data for operating air-cooled systems, although the data are likely high due to evaporative cooling operations during the daytime during summer months. An air-cooled plant without a hybrid cooling system would likely have lower consumption values than those reported here.

While operational water losses for air-cooled systems may be overestimated in the EGS scenarios, potential subsurface water losses from reservoir stimulation are not accounted for. Further research may support a reasonable estimate in the future. Nonpotable water resources may be available to meet operational water demand and mitigate reservoir fluid loss. In addition to potentially reusing geofluid from geopressured geothermal resources, other sources include water produced from oil and gas activities, water extracted from carbon capture and sequestration projects, and saline groundwater resources.

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