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The Geothermal Energy-Water Nexus

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ABSTRACT

Energy and environmental analyses are critical to developing a robust set of geothermal energy technologies that meet future energy demand. Assessments of the sustainability of geothermal power generation that have focused on resource management and associated environmental impacts during plant operations have shown that overall emissions, water consumption, and land use for geothermal electricity production have a smaller impact than traditional base-load electricity generation technologies. There is a need to improve our understanding of the environmental impacts across the life cycle of geothermal electricity systems. This paper presents an assessment of life cycle freshwater requirements of various geothermal power-generating systems. Systems evaluated included hydrothermal binary (air-cooled), hydrothermal flash, binary enhanced geothermal system (EGS) (air-cooled), flash EGS, and binary geopressured (air-cooled). On a per-well basis and a per-kilowatt-hour lifetime energy output basis, higher resource temperatures result in lower water consumption for the same technology. However, moving from binary systems that typically operate at lower temperatures to flash systems that operate at higher temperatures increases the aboveground operational loss of geofluid. In most hydrothermal systems this additional loss of geofluid is not replaced. This does not increase water consumption, but does have long-term impacts on the sustainability of the reservoir. However, in EGSs, this lost geofluid will more than likely need to be replaced to maintain reservoir pressure. The use of alternative, lower quality water sources will be important for EGSs because of the high water requirements relative to competing electricity generation systems. Finally, an analysis of relevant laws and policies was conducted as a means of identifying gaps where more information could result in better, more informed decision making with regard to geothermal energy development A new platform developed with funding from the U.S. Department of Energy's Geothermal Technologies Office — the National Geothermal Data System — is explored as an option to expand the collection and use of these kinds of data and to address these gaps.

1. INTRODUCTION

According to the Energy Information Administration (EIA) of the U.S. Department of Energy (DOE), geothermal energy generation in the United States is projected to more than triple by 2040 (EIA 2013). This addition of more than 5 GW of generation capacity is anticipated because of technological advances and an increase in available sources through the continued development of enhanced geothermal systems (EGSs) and low-temperature resources (EIA 2013). Although studies have shown that air emissions, water consumption, and land use for geothermal electricity generation have less of an impact than traditional fossil fuel–based electricity generation, the long-term sustainability of geothermal power plants can be affected by insufficient replacement of aboveground or belowground operational fluid losses resulting from normal operations.

Argonne National Laboratory (Argonne) has conducted a multi-year investigation into geothermal water consumption across a range of technologies. This analysis informs DOE's Geothermal Technologies Office (GTO) by improving the understanding of the water impacts of geothermal energy production and the role of water in the development and deployment of a robust set of geothermal technologies.

This paper examines life cycle water consumption for various geothermal technologies and closely follows methods employed in previous Argonne reports on this topic, notably Sullivan et al. (2010), Clark et al. (2011, 2012, and 2013a), and Schroeder et al. (2014). A summary of quantified life cycle freshwater requirements of geothermal power-generating systems is presented, including binary hydrothermal, flash hydrothermal, binary EGS, flash EGS, and binary geopressured geothermal systems. A brief analysis of relevant U.S. laws and policies was also conducted as a means of identifying gaps where more information could result in better, more informed decision making with regard to geothermal energy development.

2. BACKGROUND

A process-based life cycle analysis (LCA) was conducted to account for water consumption and considered activities associated with drilling, stimulation, construction, and well and power plant operations. In assessments of water use at power plants, two water quantities are commonly listed: water withdrawn and water consumed. Withdrawn water is defined as water that is taken from ground or surface water sources and may or may not be returned to the water source. It is most often associated with once-through cooling towers in thermoelectric power plants. Consumed water is water that is withdrawn but not returned to its area of extraction in liquid form. Water may be consumed through evaporation, chemical reactions, incorporation into materials (e.g., in drilling muds and cement), or injection into nonaquifer geological formations (e.g., stimulation or reservoir makeup fluids).

This analysis accounts for geofluid from the reservoir that is lost, but not replaced separately, from freshwater consumption. Losses to the atmosphere via evaporation at flash hydrothermal plants or to the formation due to reservoir characteristics may affect the long-term sustainability of such projects. They are unlikely to impact local or regional freshwater availability, however, unless supplementary injection is used to make up for these losses.

As in the previous Argonne reports, a number of hypothetical geothermal power plants were evaluated during the LCA. A standardized set of scenarios, with the exception of geopressured geothermal systems, were developed by the GTO with input from national laboratory and industry experts (see Table 1) for evaluation of the levelized cost of electricity (LCOE) and the associated environmental impacts of geothermal technologies. These scenarios were provided by the GTO for consistency between this and any other analyses that might rely on these scenarios such as Sullivan et al. (2013). The scenarios were run in DOE's Geothermal Electricity Technology Evaluation Model (GETEM) repetitively to create a range of possible outcomes by varying select parameters (DOE 2011a). Key parameter values from the scenario definitions and select GETEM outputs were then used to help calculate the life cycle water consumption for each scenario. These included, but were not limited to, the number of production and injection wells, the well flow rates, the water consumption for flash system cooling, subsurface water loss for EGS, and plant lifetime.

Table 1: EGS, Hydrothermal, and Geopressured Scenario Details

	Binary Hydrothermal Air-Cooled	*Flash Hydrothermal Wet-Cooled*	*Binary EGS Air-Cooled*	*Flash EGS Wet-Cooled*	*Geopressured Air-Cooled*
Power sales (MW)	15–50	30–50	10–40	25–50	3.6 MW Geothermal Electric; 17.4 MW Natural Gas Thermal Power
Generator type	Binary	Flash	Binary	Flash	Binary
Cooling type	Air	Wet	Air	Wet	Air
Temperature (°C)	140 or 175	175 or 225	100, 150, or 175	250 or 325	130–150
Well depth (km)	1.5 or 2.5	1.5 or 2.5	2, 2.5, or 3	3.5 or 4	4-6 (Production); 2–3 (Injection)
Injection to production ratio	0.75	0.75	0.5	0.5	NA
Production flow rate (kg/s)	100	80	40 or 100	40 or 100	35–55
Subsurface water loss (% produced flow)	NA[a]	NA	1 or 5	1 or 5	NA
Plant lifetime (yr)	30	30	20 or 30	20 or 30	20

[a] NA = not applicable.

The parameters for analyzing geopressured geothermal systems were developed with input from industry experts, GTO, and well field characteristics from the first hybrid geothermal geopressured geothermal power plant in the United States, Pleasant Bayou in Brazoria County, Texas (Randolph 1992; DOE 2010; Luchini 2011). Geopressured geothermal power plants take advantage of underground pressurized reservoirs that contain both hot water and dissolved natural gas (Clark et al. 2011). The resource base includes thermal energy, mechanical energy, and chemical energy (in the form of methane). Pleasant Bayou generated electricity from the geofluid and separated the natural gas to test both the production of electricity from combustion in an on-site hybrid power system and the processing of natural gas to direct-to-sales pipelines (DOE 2010; Randolph et al. 1992).

3. METHODOLOGY

The different life cycle stages represented in this analysis are Drilling and Construction, Simulation and Circulation Testing, Belowground Operational Losses, and Aboveground Operational Losses.

The first stage, *Drilling and Construction*, includes all water consumed during well drilling, pipeline construction, and power plant construction. As in previous analyses (Clark et al. 2010, 2011), this stage does *not* include the wellhead apparatus, but instead, all components belowground, including all liners and casings. Pipelines include pipeline, pipeline supports, and support footings.

The *Stimulation and Circulation Testing* stages are more straightforward and include consumptive losses from all fluids injected underground for the purposes of stimulating an EGS reservoir, and then, subsequently, testing the circulation of this enhanced reservoir. Although additives, such as tracers, diverters, chelating agents, and several others, are present in these fluids (see Clark et al. 2013a for more information on chemicals used in stimulation activities), it was assumed for the purpose of this analysis that the volumes are 100% water. This is because while additives may be present, they typically represent a small percentage of the total fluid sent downhole (Clark et al. 2013a).

Belowground Operational Losses, otherwise known as reservoir loss, were assumed to be either 1% or 5%, depending on the scenario analyzed. These values are based on past research into actual losses at real-world EGS projects, which showed these values to be within the range experienced at these facilities (Chabora et al. 2012; Portier et al. 2009; Zimmermann and Reinicke 2010; Schindler et al. 2010). Although higher loss rates have been observed at feasibility testing sites, it is unlikely that utility-scale projects would be practical at high loss rates.

Finally, *Aboveground Operational Losses* are represented by two distinct categories: Cooling-Related Losses and Non-Cooling Associated Loss. *Cooling-Related Losses* include all water consumed during cooling-related operations of the plant itself, while *Non-Cooling Associated Losses* is a category intended to encompass all other losses not included in the other life cycle stages. It is a constant value of 40 gallons per MW. This value is based on the average water consumption of a dry-cooled binary system, which because the cooling system does not consume any water, represents the water consumption from non-cooling related activities, such as dust suppression, maintenance, and domestic use (BLM 2010; CEC 2008; DOE 2011b; Geodynamics 2011; Kagel et al. 2005).

4. RESULTS

Table 2 summarizes water consumption by life cycle stage for EGS, hydrothermal, and geopressured scenarios,

Table 2: Total and Freshwater Consumption by Life Cycle Stage for Various Geothermal Technologies

	Binary Hydrothermal Air-Cooled	*Flash Hydrothermal Wet-Cooled*	*Binary EGS Air-Cooled*	*Flash EGS Wet-Cooled*	*Geopressured Air-Cooled*
Drilling and construction loss (gal/MWh)	0.49–2.0	0.64–1.0	0.8–9.0	0.40–2.0	0.4
Stimulation water consumption (gal/MWh)	0	0	1.9–32	0.8–4.7	0
Circulation testing water consumption (gal/MWh)	0	0	1.8–29	0.0–4.2	0
Belowground operational loss (gal/MWh)	0	0	190–4,100	49–490	0
Cooling-related losses (gal/MWh)	0	0	0	1,500–2,300	0
Non-cooling associated consumption (gal/MWh)	40	40	40	40	0
Totals					
Freshwater consumption (gal/MWh)	40–42	41	44–110	41–51	40
Geofluid loss (gal/MWh)	0	2,500–3,600	190–4,100	1,500–2,700	23,700
Geofluid makeup (gal/MWh)	0	0	190–4,100	1,500–2,700	0
Water consumption (gal/MWh)	40–42	41	230–4,200	1,600–2,800	0

4.1 Operational Losses versus Construction and Drilling Losses

Overall, the water loss for the construction and drilling phase was found to be extremely small when compared with the total water loss for all scenarios analyzed. For the EGS scenarios, consumptive losses from drilling and construction composed between 0.02% and 0.34% of the total water consumption for each scenario. These percentages went up slightly for the hydrothermal scenarios, with well drilling and construction making up 1.2% and 4.8% of total water consumption. These findings are in line with previous findings, which suggest that operational losses are by far the major contributor to geothermal water consumption (Clark et al. 2011, 2013a).

4.2 Binary EGS versus Flash EGS

In all EGS scenarios, losses from the operational phase dominated, both aboveground and belowground. For the air-cooled binary EGS scenarios, belowground reservoir loss dominated and accounted for 80.6% to 97.4% of the total water consumption. For wet-cooled flash EGS scenarios, aboveground operational losses dominated. This is due to significant makeup water losses in the flash system scenarios, between approximately 23% and 30%, depending on the scenario according to GETEM. These losses occur because of (1) flashing of the geofluid and incomplete condensing of the fluid, and (2) the wet cooling system assumption used for these systems, that is, that a portion of the produced geofluid condensate will be diverted to cool the system. Some of the condensate used for cooling water is lost via the cooling tower through blowdown, drift, or evaporative losses. Binary systems that are air-cooled do not experience these losses.

4.3 Hydrothermal Binary versus Flash

For binary hydrothermal scenarios, non-cooling associated losses dominated at greater than 95% for all scenarios. For flash hydrothermal, although no freshwater consumption due to cooling is reported in Table 2, there is significant geofluid loss because of cooling ranging between 2,500 gallons per megawatt hour (gal/MWh) and 3,600 gal/MWh. This is a result of flash hydrothermal systems relying on condensate, not freshwater, for cooling. In these systems, flash losses of geofluid were not replaced with freshwater.

Although this leaves the long-term sustainability of the reservoir vulnerable, it is common industry practice to not replace lost geofluid or to replace a fraction of lost geofluid. Therefore, one can see that for those systems, geofluid losses were high, but total freshwater consumption was actually very low, particularly when compared with EGSs. However, at least two operating flash hydrothermal plants, Coso and Dixie Valley, do have existing supplementary injection augmentation programs that utilize fresh groundwater to make up for lost geofluid (BLM and U.S. Navy 2008; NDWR 2012). In these cases, freshwater consumption is significantly higher, approaching the quantity of geofluid lost.

4.4 Water Losses

As mentioned previously, the differences in water consumption between the EGS and Hydrothermal scenarios were largely due to the differences inherent in these two technologies. EGS projects must first inject water underground to create a reservoir. Maintaining sufficient reservoir volume and pressure to successfully circulate fluid requires significant volumes of water through the life of the project as belowground fluid losses are expected to vary from 1% to 10%. In contrast, hydrothermal systems do not have this issue. Binary hydrothermal scenarios, which can rely on air-cooling, consume relatively little water.

In comparing water consumption between these technologies, the model shows that EGS binary systems consume between 230 gal/MWh and 4,200 gal/MWh, whereas hydrothermal binary systems consume between 40 gal/MWh and 42 gal/MWh. For flash systems, this difference between hydrothermal and EGS resources is also very pronounced, due to much of the fluid loss in the hydrothermal scenarios being attributable to geofluid loss and not to actual freshwater consumption. Flash hydrothermal water consumption is 41 gal/MWh and flash EGS water consumption ranges from 1,600 gal/MWh to 2,800 gal/MWh. However, this difference will shrink significantly for flash hydrothermal systems where makeup fluid is injected to improve the sustainability of the reservoir. This process was not directly modeled, but the quantity of water that would be required can be inferred from the calculated total geofluid loss values.

On a per-well basis and a per-megawatt-hour lifetime energy output basis, geopressured geothermal systems appear to consume less water than other geothermal technologies (Clark et al. 2012). The geopressured results are allocated between geothermal electric power generation (3.6 MW) and natural gas thermal power generation (17.4 MW), because both are produced from the system. This allocation results in less water consumption per MWh lifetime energy output for the geothermal system. If all of the water consumption in plant construction were allocated to the geothermal electric system, the water consumption would be larger per MWh lifetime energy output. Allocating all of the water consumed to the geothermal electric system would make the geopressured geothermal systems more water-intensive in the construction stage than the hydrothermal systems because of the lower geothermal power generation potential of the cooler geopressured geothermal resource. Overall water requirements for geopressured systems across the lifetime are low, because maintaining reservoir pressure is not a long-term goal of these systems. Significant geofluid losses do occur above ground for geopressured systems with the reinjection of geofluid in a non-pressurized aquifer (23,700 gal/MWh of geofluid loss), typically a disposal well, although opportunities for reuse of the geofluid should be explored. Although geopressured systems are likely to have aboveground operational consumption that is non-cooling related (similar to other systems), data for geopressured systems are insufficient to reassess at this time.

4.5 Impact of Resource Temperature

Lower temperature resources require higher total flow rates to generate the same amount of energy. This directly affects two variables that impact water consumption—belowground operational losses for EGSs and the number of wells required to generate the same amount of power. Given that operational losses make up the majority of water consumption for most geothermal systems, the impact on belowground operational losses is far more significant to the overall water requirements than the impact of the number of wells drilled. For EGSs, where the resource temperature is high enough that flash systems are recommended or required, the water consumption is significantly greater than for binary EGS because of the additional aboveground operational losses associated with the wet-cooled flash systems, which are typical for systems with higher resource temperatures.

4.6 Comparison with Other Energy Technologies

The results show that total fluid consumption for most scenarios is quite high relative to most energy systems, with a low of 40 gal/MWh for hydrothermal binary and a high of 4,200 gal/MWh for EGS binary. However, there are opportunities for the use of freshwater alternatives. Although water consumed for drilling, stimulation, and aboveground non-cooling operational uses can be assumed to be freshwater, water injected into the formation to compensate for aboveground or belowground operational losses need not be fresh and must only be chemically compatible with the formation and the injection well materials. Thus it is possible that many degraded or lower quality water sources can be utilized for these purposes, thereby reducing the impact of geothermal systems on freshwater resources (Schroeder et al. 2014). Accounting for alternative waters, the consumption of fluid that would typically be freshwater for most of the scenarios is approximately 40 gal/MWh to 50 gal/MWh, which is significantly less than most thermoelectric generation technologies and on par with other renewables such as solar and wind (Vestas 2006; Harto et al. 2010; Macknick et al. 2011; DeMeo and Galdo 1997). Photovoltaic (PV) solar consumes between 70 gal/MWh and 190 gal/MWh over the life cycle, while concentrated solar power (CSP) consumes between 870 gal/MWh and 1,120 gal/MWh. Water consumption comparisons between different energy technologies can be seen in Table 3.

In comparing water consumption between the reference and improved scenarios, it becomes apparent that although water consumption for the hydrothermal scenarios is fixed at approximately 40 gal/MWh, because of the non-cooling associated consumption discussed previously, there are significant water savings between the reference and improved cases for the EGS scenarios. This is largely due to improved control of the reservoir in the improved scenarios. Reservoir loss drops from 5% to 1% between these cases, and since this is the largest contributor to water consumption for EGS, it follows that improving that parameter would positively affect the water consumption numbers, as indeed is the case here.

Table 3: Comparison of Water Consumption by Energy Technology

Energy Technology	Water Consumption (gal/MWh)
Geothermal (hydrothermal binary)[a]	40
Geothermal (hydrothermal flash)[a]	40[b]
Geothermal (EGS binary)[a]	230–4,200
Geothermal (EGS flash)a[a]	1,600–2,800
Geothermal (freshwater average)[a]	40–50
Geothermal (Meldrum)[c]	5–720
Geopressured [i]	0.40
Wind [c, d]	1–10
Solar (PV) [e, f, g]	70–190
Solar (CSP) [c, e, f, g]	160–1,120
Coal [f]	100–1,100
Nuclear [f]	100–845
Natural Gas [h]	80–620
Shale Gas [h]	110–670

a - From this analysis, b - Only includes freshwater, not geofluid consumption, c - Meldrum et al. (2013), d - Vestas (2006), e - Harto et al. (2010), f - Macknick et al. (2011), g - DeMeo and Galdo (1997), h - Clark et al. (2013b), i - -Clark and Harto (2013)

4.7 Data Gaps

A comprehensive picture of water use in U.S. geothermal energy production is inhibited by the challenges of navigating the bureaucracy surrounding geothermal energy production. These oversights can lead to gaps in knowledge, and, consequently, data, particularly surrounding water consumption. When analyzing the sources of water for different geothermal energy stages, significant variability was observed at the state and federal levels regarding what constitutes a geothermal resource and the extent that it is different from a water resource (e.g., groundwater) (Schroeder et al. 2014).

In addition, recent discussions with state officials and industry representatives have also called into question the precision and value of production and injection data for determining freshwater consumption from geothermal power plants (Clark et al. 2013a). Often these data are reported based upon a single monthly point measurement of flow rates and temperatures rather than monthly averages, which can introduce monthly variability into the data. There is also the potential for error in converting between mass flows and volumetric flows. For example, since total dissolved solids (TDS) are not reported, they had to be estimated and were assumed to be constant (between production and injection) when performing the required density corrections. Furthermore, failure and calibration issues with flow meters have been suspected as a common issue with the reported production and injection data.

Finally, geothermal's complicated permitting structure also presents a significant challenge to understanding water use at geothermal power plants (Schroeder et al. 2014). In Nevada, for example, while water permits are publicly available online through the Division of Water Resource's web portal, the permits are not organized by plant, but rather, by applicant. This grouping may make sense up front, however, in the analysis presented in this paper, it was not unusual for one facility to have multiple applicants, some of which used different names for the same facility. In addition, a plant may acquire old permits from water in the vicinity or apply for new water permits. Geothermal companies also sometimes prospectively apply for water permits years before construction of a plant begins, often through shell companies or limited liability corporations (LLCs), whose name may have nothing to do with the facility's name. Navigating through all of this information and trying to track down all the permits that may apply to one site is extremely difficult, and the results may lead to errors in calculating water consumption numbers.

4.8 National Geothermal Data System

The National Geothermal Data System (NGDS) represents a potential solution to the issues identified in this analysis. Funded by DOE's Geothermal Technologies Office, this distributed data system, accessed from a single website (www.geothermaldata.org), links geothermal data repositories across the United States and other countries. The NGDS contains geothermal data and information contributed by private industries, state and federal agencies, and businesses. It allows users to search for location-specific and other geothermal information. From the NGDS website, this resource can be used to "determine geothermal potential, guide exploration and development, make data-driven policy decisions, minimize development risks, understand how geothermal activities affect your community and the environment, and guide investments." New data are being provided regularly. If not already provided, this distributed information system also hosts information about drilling volumes, operational water consumption, and other geothermal water information, and thus provides a crucial tool. Voluntary and mandatory reporting of hydraulic fracturing fluids used in oil and gas development are managed through FracFocus 2.0 (http://fracfocus.org) and may serve as an example of the type of fluid data that could be reported to the NGDS.

For example, the Arizona Natural Resources Review Council unanimously approved adoption of a plan for developing a Natural Resources Decision Support System (NRDSS) to link data, documents, and geographic information system (GIS) layers with its nine agencies dealing with natural resources, environmental issues, and transportation, and with corresponding federal agencies. The system will be built around the U.S. Geosciences Information Network (USGIN), a data integration framework that underlies NGDS. Arizona's Governor is poised to implement the system. USGIN will have three integrated components: it will contain the Arizona GIS repository and clearinghouse (AZGEO); it will be a single point of contact (SPOC) (i.e., the designated source) for information for federal agencies operating in Arizona; and it will be a system clearinghouse for discovering, accessing, and integrating documents and data that will be available via system and agency web portals through online catalogs. As is the case for NGDS, each data provider will maintain control of its own data, documents, and maps and will make them accessible through web services provided via a distributed network. The federal agencies will share their materials from a node on the system created under the auspices of the Western Regional Partnership, a consortium of more than 20+ federal agencies and governors of 5 western states. The system can be expanded to include other agencies. According to the Arizona Geological Survey, this will be the first interoperable network of state natural resources data in the country, the first digital SPOC, and the first federal-state system that meets the requirements of the White House Open Data Access initiative.

5. SUMMARY AND CONCLUSIONS

The geothermal water life cycle scenarios have been updated to be consistent with the current LCOE scenarios used by GTO. These scenarios include a more complete exploration of the parameter space of possible geothermal power plants and allow for a more thorough examination of the impact of key factors on life cycle water consumption. The most important of these factors was shown to be resource temperature. In general, higher resource temperatures result in lower water consumption for the same technology. However, going from binary systems that typically operate at lower temperatures to flash systems that operate at higher temperatures results in a large jump in the aboveground operational loss of geofluid. In most hydrothermal systems, this additional loss of geofluid is not replaced, which does not increase water consumption, but it does have long-term impacts on the sustainability of the reservoir. In EGSs, however, this lost geofluid will more than likely need to be replaced to maintain reservoir pressure. The use of alternative, lower quality water sources will be important in these cases because of the high water requirements relative to competing electricity generation systems. Another option for reducing water impacts would be the use of binary systems for higher temperature EGS resources than are traditionally used for hydrothermal resources. This option is likely to be most viable for EGS resources more than 200°C but lower than 300°C, such as the 24-MW binary facility Ormat operates in Zunil, Guatemala, which has a resource temperature of 300°C (GRC 2003). Data and information sharing through the National Geothermal Data System can help reduce the upfront risk of geothermal development by making key environmental and geothermal resource data available to geothermal developers as well as researchers. Spending less time finding data and more time using it to foster geothermal development solutions is key.

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