Chapter 10

Environmental Considerations and Impact

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When compared with other renewable sources of energy, geothermal energy has low carbon emissions rate, the smallest surface footprint, and low potential for water contamination.

I. Introduction

All energy technologies, from traditional fossil based sources to renewables like solar and wind, have some environmental impact. When we seek to understand and quantify those impacts across the various sources, ultimately we should consider more than the energy production operation itself. Impact should be measured beginning at the supply chains used to manufacture and support the technologies, and also include end of life outcomes related to each, like recyclability, disposal, and waste. It is important as we navigate our energy transition over the coming decades that we proceed with thoughtful, fact based analysis of the impacts and externalities of each energy technology we seek to adopt, deploy, and scale. Without considering the full life-cycle environmental impact of emerging energy technologies, including renewables, the risk of unintended environmental consequences will grow substantially, potentially offsetting the gains we seek as we build our future.

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II. Past Research on the Environmental Impact of Geothermal

In 2006, an influential report was commissioned by a panel of experts, and published by the Massachusetts Technology Institute ("MIT") to assess the future of geothermal energy, focusing on Engineered (or Enhanced) Geothermal Systems ("EGS") in the U.S (Tester, et al., 2006). The report, entitled *The Future of Geothermal Energy*, was a ground-breaking, seminal, and visionary work that remains today the most encompassing and high impact report conducted about geothermal in the world.

The Future of Geothermal Energy included a chapter on the environmental impacts of geothermal. The authors discussed several environmental aspects (both positive and negative), including water, air, and thermal pollution, water use, and induced seismicity. They referenced a number of works that significantly influenced the conceptual thinking of geothermal. In their analysis, a consensus of scientists found that geothermal has a lower environmental impact than all other fossil energy sources, and possibly lower than other renewables (Tester, et al., 2006). Since then, several papers have considered the broader environmental impacts of conventional geothermal technologies, focusing in particular on Conventional Hydrothermal Systems and thermal networks (Sayed, et al., 2021; Bošnjaković, et al., 2019; Bayer, et al., 2013). Bayer, et al. (2013) found that comprehensive datasets on the environmental impacts of these conventional geothermal technologies are lacking, and that full life-cycle assessments are generally restricted to the western United States (e.g., the Geysers site). Bošnjaković, et al. (2019) considered a broad range of possible environmental impacts, given the potential for geothermal to be developed and deployed in Croatia. They compared geothermal with traditional fossil fuel powered generation (coal, oil, and gas), and showed that carbon dioxide ("CO2") and nitrogen oxide ("NOX") emissions, as well as surface footprint, were considerably lower for geothermal, though the release of waste heat was much higher in the case of conventional geothermal plants.

In a recent study, Sayed, et al. (2021) compared a number of renewable technologies with geothermal, and reported that the most significant environmental impacts implicated by geothermal included the potential for land subsidence, induced seismicity, higher water use, and surface footprint, a few of which are prevalent in other energy systems.

Although all energy sources are accompanied by some environmental impacts, the consensus produced by The Future of Geothermal Energy report provides an important foundation to this analysis. Geothermal development and deployment results in lower environmental impact than other energy sources, especially fossil and nuclear energy, partly because the fuel cycle (i.e., subsurface heat) lies immediately below the generating plant, therefore physical mining is not required, and the fuel requires no processing, as is the case for gas and nuclear fuel sources. Importantly also, The Future of Geothermal Energy predated the significant technology developments that are now enabling the next generation of geothermal technologies, like Advanced Geothermal Systems/Closed Loop Geothermal Systems ("AGS"), which hold promise for even less environmental impact.

III. Subsurface Exploration and Resource Development

The exploration and drilling phases of geothermal development carry environmental concerns distinct from the operational phases. Potential exploration and development impacts for geothermal projects may implicate water (e.g., quantity, groundwater contamination, disposal, and remediation), induced seismicity, and land subsidence caused mainly by fluid withdrawal. We will examine these in turn.

A. Water and Fluid Management

Techniques and approaches used for drilling wells for geothermal are nearly identical to those of any mud-rotary drilled oil and gas well, with some variations depending on the particular geothermal concept. Well drilling requires water and (commonly) some type of bentonite-rich additive that increases viscosity enough to return drill cuttings to the surface.

As is also the case in the oil and gas context, drilling processes require a number of necessary environmental considerations that range from identifying a water source with sufficient volumes, managing fluids with potentially dissolved contaminants or cuttings, and ensuring that local groundwater resources are not impacted by the drilling and completion processes.

Before diving into water implications of drilling processes, it may be useful to put the broader operational context of water use for geothermal into perspective. Figures 10.1 and 10.2 below place the scale of water consumption impacts associated with geothermal operations, as compared with other energy sources, into perspective.

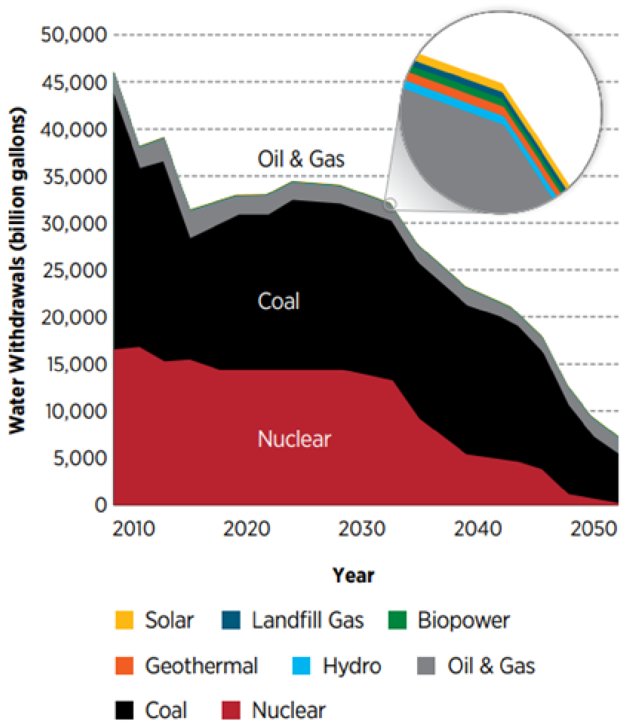

Figure 10.1. Power-sector water-withdrawal impacts in billions of gallons (1 gallon=3.8 liters). *Source: Adapted from Millstein, et al. (2019).*

B. Water for Well Drilling and Hydraulic Stimulation

According to the U.S. Energy Information Agency, nearly 1,000,000 oil and gas production wells are in operation today, and many more have been drilled over the last 100 years, each of these wells required water for drilling (EIA, 2021). Depending on the region of the country (more humid East Coast versus drier Southwest), water may be more or less plentiful and/or readily available. A more recent history of horizontal drilling indicates that the volume of water used for drilling and cementing oil and gas wells is about 380,000 gallons per well (Scanlon, et al., 2014). If the well were to require hydraulic stimulation, then the volume needed could increase tenfold. These numbers have increased with time because subsurface engineering in the form of horizontal laterals have increased in length, and now approach 10,000 feet (1.9 miles or three kilometers) or longer.

Wells drilled for geothermal energy production would need to identify and source similar volumes of water, especially for EGS, which also can use a form of hydraulic fracturing (DOE, 2012). For new types of geothermal technologies, such as AGS, the volume of water required for the drilling and cementing of wells should be similar to that of recent experiences with horizontally drilled wells without stimulation. In nearly all cases, wells drilled to substantial depths require fluids augmented with bentonite or other additives that increase viscosity to entrain cuttings, cool the drilling bit and pipe, and maintain borehole stability.

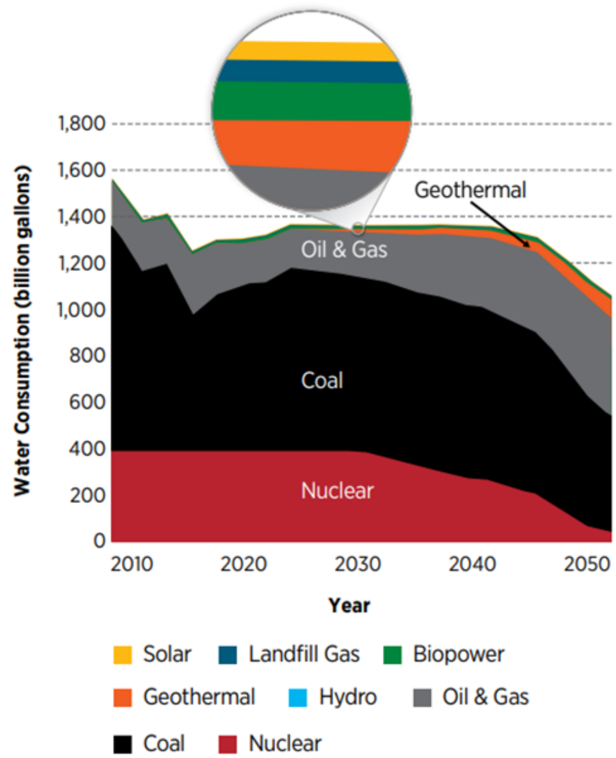

Figure 10.2. Water-consumption impacts from the geothermal power section in billions of gallons (1 gallon=3.8 liters) under the Technology Improvement scenario. *Source: Adapted from Millstein, et al. (2019).*

Depending on bottom-hole temperature, fluids and cuttings that return to the surface from a hot reservoir need to be cooled before being recirculated downhole. In some cases, long-term exposure to elevated temperatures greater than 150 °C (302 °F) could increase the viscosity of bentonite, potentially clogging pipes, and leading to degraded circulation. Use of high temperature resistant polymers could reduce this potential. An excellent source of information on the drilling of hot geothermal wells is found in Pálsson, et al. (2014) and Friðleifsson, et al. (2014), along with other articles in that special issue of Geothermics. Figures 10.1. and 10.2 detail water withdrawal and water consumption impacts, separated by power sector. Regardless of the technology, the potential for local impacts requires careful analyses using location specific data and information.

Since around 2005, a combination of directional drilling and hydraulic fracturing (also known as frac'ing) has become a game changer in oil and gas exploration and development. Not surprisingly, the practice has undergone significant innovation and improvement in the nearly 20 years since widespread use began, including a new understanding of the chemical additives used in the process. In general, frac fluids are dominated by water and proppants (particles used to wedge open fractures), often sand, but sometimes mixed with chemicals to inhibit corrosion and scaling, reduce friction along the inside of the drilling pipe, and reduce biological buildup. The FracFocus (2021) Chemical Disclosure Registry, which is managed by the Ground Water Protection Council and Interstate Oil and Gas Compact Commission, has become a necessary tool for governments, industry, and the general public in obtaining information on fracturing fluid chemistry. Although not all chemical concentrations are disclosed due to intellectual property concerns, the Registry is a significant step forward in transparency.

C. Potential Pathways of Water Contamination

Similar to any well drilling, especially for oil and gas exploration, some wastewater and waste material are generated, ranging from drilling cuttings, to drilling mud, to associated wastewater, when geothermal projects are developed. Moreover, the methods of management and safe disposal are also similar. Many lessons have been learned and best practices established that minimize the potential for inadvertent release, and that improve our understanding of the pathways leading to contamination of land, surface water, or groundwater.

As indicated earlier, typical drilling waste can contain, aside from rock cuttings, bentonite, polymers (e.g., polyacrylamide), and salts. Depending on the concentration of these chemicals and constituents leached from the host rock, post-processing of the water could remove dissolved constituents for alternative industrial uses. If not, and specific regulations in the state, province, or country allow, land application of these waste products may be allowable with appropriate permits.

Recently, the Environmental Protection Agency ("EPA") released a comprehensive report that described water cycle impacts from hydraulic fracturing operations in the United States (EPA, 2016) in the oil and gas context. The EPA concluded that hydraulic fracturing operations can impact water resources (both groundwater and surface water) under some circumstances, with severity depending on a number of considerations. Primary pathways include surface spills of fluids, poor well casing or cement integrity, and improper design leading to injection of fluids into groundwater resources. In general, a lack of relevant pre and post frac'ing groundwater monitoring has hindered our ability to quantify the extent and severity of groundwater contamination resulting from unconventional oil and gas operations.

Findings from the fossil fuel industry are relevant to geothermal development because the technologies for well drilling and frac'ing are similar to those of oil and gas operations. However, utility scale geothermal operations (as opposed to smaller scale and localized technologies, like heat pumps) have a relatively shorter history with fewer examples, and for some technologies, no existing case studies. For example, the proppant material used during stimulation activities requires substantial excavation and, in some cases, water resources to mine and process the sand. One recent analysis found that a total of 10,000 to 40,000 acre feet per year of water was being consumed for proppant mining in west Texas, or between 60 and 250 gallons of water per ton of sand (Mace & Jones, 2021). Depending on the climate of the region and the number of wells to be stimulated, the volume of water could be significant.

Authors note that the hydraulic fracturing envisioned in many Next Generation EGS concepts are of a different nature and magnitude than oil and gas, but as these methods are generally in the prototype stage, there is little data to allow a thorough analysis. As data emerges from pilot projects, further study will be needed.

D. Risk, Monitoring, and Mitigation of Induced Seismicity

Induced seismicity from fluid injection into the subsurface has become a topic of significant public concern and research since around 2010, after a significant uptick in seismicity in the southern midcontinent of the United States. Research has shown that oilfield operations for enhancing oil and gas production from shales and other tight rocks are responsible for a significant portion of the seismic activity. Media attention, public meetings with hundreds of attendees, and findings from initial research papers that yielded more questions than answers have led to responses by individual states, ranging from new regulations to deployments of state run seismic monitoring programs that could deliver near-real-time data on earthquake occurrences. For example, in Texas, the State seismicity-monitoring program ("TexNet") is run by the Bureau of Economic Geology at The University of Texas at Austin, in which a catalog of seismic activity (TexNet, 2021) is publicly available and used by industry, regulators, researchers, and others.

Several other states run seismic networks, as well as the U.S. Geological Survey. As described by Ellsworth (2013) and Rubenstein and Mahani (2015), earthquakes can be induced when fluids are injected into the subsurface, including water for hydraulic fracturing or wastewater disposal, or gasses (often CO2) for enhanced oil recovery (Gan & Frohlich, 2013). State agencies that regulate oil and gas exploration and production (e.g., the Texas Railroad Commission) typically lead regulatory responses that can include well shut-ins, reduction of injection volumes or rates, modifications of depth of injections, requirements for enhanced reporting of injection practices (rates, volumes, downhole pressures), and/or requirements for enhanced monitoring of seismicity through deployment of seismometer stations proximal to the injection well. In Texas, the main driver of induced seismicity has been found to be deep well injection of wastewater or hydraulic stimulation, depending on the basin in question (Savvaidis, et al., 2020; Hennings, et al., 2019; Scanlon, et al., 2019; Walter, et al., 2018). The potential for induced seismicity by basin in Texas is considered in further detail in *Chapter 4, The Texas Geothermal Resource: Regions and Geologies Ripe for Development of this Report*.

Although originally not thought to induce seismic events, hydraulic fracturing has more recently been identified as a causal factor, especially when hydrocarbons are being sought in shales or other tight rocks. In hydraulic fracturing in the geothermal EGS context as it exists today, fluid is injected into rocks to open pre-existing fractures, thus enhancing rock permeability (DOE, 2012).

Recently, research was conducted on EGS and seismicity to explain where and when injection activities could lead to earthquakes. For example, Cladouhos et al. (2015) reported on a field demonstration project in which certain materials, thermally degradable zonal isolation materials ("TZIM"), could be used to isolate permeable zones so that hydraulic fracturing of low permeability zones would be more effective. In their field demonstration conducted in Oregon, workers recorded nearly 400 events, ranging in magnitude from M0 to M2.26, all below levels of seismicity perceived by humans. Research has also been conducted in Switzerland (Deichmann & Giardini, 2009), in which 11,500 cubic meters of fluid was injected into a 3.1 mile (five kilometer) deep borehole, resulting in 10,000+ recorded events in a period of about one week, the maximum event being recorded at M3.4. Although the well was opened to relieve pressure, events were recorded intermittently for two years.

Majer, et al. (2007) reported on knowledge and gaps (at that time) in geothermal induced seismicity, reviewing several case studies from sites in the United States and elsewhere (e.g., the Geysers site near San Francisco; Cooper Basin, Australia; Berlín, El Salvador; France). In general, and consistent with other studies, (Xie, et al., 2015; Grunthal, 2013), findings show that creating permeability in EGS reservoirs through hydraulic fracturing does lead to the onset of induced seismicity, although careful planning and knowledge of subsurface fault stress, proximity to basement rock, and pressure control during injection can control the magnitude of events to levels below what can be felt by humans.

To be sure, the general public has a heightened awareness of the potential for inducing earthquakes from energy development, particularly oil and gas, and has called upon regulators to adopt measures that will mitigate future events and reduce earthquake hazard and risk from injection. For example, the Alberta Energy Regulator (AER, 2015) adopted a regulatory approach, known as a traffic light protocol or some variation, which mandates a potential range of actions on the basis of recorded magnitudes of events that are proximal in time and space to injection activities. Other energy producing states have adopted similar actions. A similar approach was proposed at the recent PIVOT2022 geothermal conference for application in geothermal contexts, followed by a panel of experts who discussed the topic in detail (PIVOT 2022; 2022). Robust data sharing and standardization of processes were discussed by the panel as an essential foundation of knowledge for managing seismicity risk in geothermal development. Other actions to mitigate events can range from enhanced seismic monitoring to ceasing operations, based on the magnitude of earthquakes detected. Kim, et al., (2018) adopted protocols suggested by the DOE for earthquakes induced by injection, while correcting for quarry blasts and noise from transportation.

When these protocols, or other controls, were instituted by regulatory agencies responsible for oil and gas permitting, earthquake occurrences decreased. In Oklahoma, for example, which experienced perhaps the largest ramp up of seismic activity from fluid injection, the Oklahoma Corporation Commission issued regional directives to reduce injection of fluids into formations (e.g., the Arbuckle Formation) near the crystalline basement, mandated plugback of hundreds of disposal wells, increased reporting of fluid disposal by operators, and created digital tools that provided significantly more and timely information on earthquakes and injection volumes and pressures (OCC, 2021a). As a result, earthquake rates and magnitudes have decreased significantly over the last five years (OCC, 2021b), partly from reduced injection (as a result of lower oil and gas prices) and partly from these controls, illustrating the value in proactive management of injection activities that can be applied to geothermal systems.

It is important to note that although Conventional Hydrothermal Systems do re-inject used water, these systems have injector and producing wells, and are ideally operated in equilibrium between the two. This is in contrast to wastewater injection in oil and gas, the origin of much of the induced seismicity experienced by industry, which does not involve producing any fluids in conjunction with injection. Further, induced seismicity concerns are associated primarily with Open to Reservoir geothermal concepts, such as Conventional Hydrothermal Systems ("CHS"), and EGS. Next generation geothermal concepts, particularly non-hydraulic fracture based systems such as AGS and some Hybrid Geothermal Systems, in which fluids are not injected into, or pumped from, subsurface reservoirs, should carry low induced seismicity risk. This is particularly true as compared with oil and gas operations that require extensive hydraulic stimulation or significant disposal of oilfield wastewater through injection. This is an area that will require more study as next generation geothermal concepts, several in pilot phase currently, produce field data.

E. Potential for Land Subsidence

In general, if fluid removal rates and volumes exceed reinjection rates and volumes, subsurface reservoirs could consolidate, leading to land subsidence observed at the surface. Land subsidence can be a significant concern. First, surface and/or near-surface infrastructure (e.g., buildings, foundations, pipelines, roads) could be damaged, depending on subsidence severity, including the geothermal infrastructure itself. Second, consolidation of reservoirs reduces available pore space, fracture apertures, and fracture pathways for fluid storage and movement, which could decrease the efficiency or operability of the geothermal system.

The potential for subsidence depends on the type of geothermal technology, whether a Conventional or Next Generation system. Large geothermal fields using traditional fluid management (i.e., injector-to-producer movement of fluids) need to manage pressures carefully to avoid positive void ratios that might lead to local (or larger) subsidence. For example, Allis (2000) reported on Wairakei field in New Zealand, where a maximum subsidence of 46 feet (14 meters) was measured. New Closed to Reservoir geothermal concepts, particularly AGS and some Hybrid Geothermal Concepts, in which water is not withdrawn from the reservoir itself, should not alter subsurface pressure regimes, thus avoiding subsidence.

IV. Power Plant Operations

Potential environmental impacts related to geothermal plant operations and maintenance ("O&M") include water, air, solids (heavy metals and/or other contaminants), land use, traffic, and noise. We will consider each in turn.

A. Water and Fluid Management

Produced fluid management during geothermal plant operations depends primarily on the type of plant under consideration. We will consider Conventional

Hydrothermal Systems ("CHS") and Engineered Geothermal Systems ("EGS"), which are both Open to Reservoir systems, and Advanced Geothermal Systems/ Closed Loop Geothermal Systems ("AGS"), which are Closed to Reservoir systems.

1. Open to Reservoir Systems

Open to Reservoir Systems, for the purposes of this Report, are those in which the working fluid comes in direct contact with subsurface reservoir, flowing from an injection well through the rock to a production well (Figure 10.3).

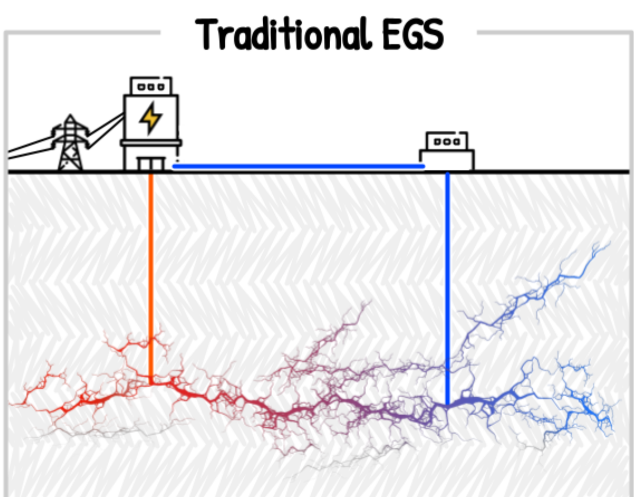

Figure 10.3. An open to reservoir geothermal system. Shown is a traditional EGS concept. *Source: The Future of Geothermal in Texas, 2023.*

The fluid might be sent through heat exchangers of different types to convert the energy contained in the heated fluid into steam, which turns the turbine to generate electricity. After generating power, the fluid is then run through a cooling tower or facility, and then pumped back down into the subsurface to gather more heat.

As discussed in detail in Chapter 1, Geothermal and Electricity Production of this Report, Open to Reservoir Systems, like EGS and CHS, operate using a network of natural or engineered fractures, created via hydraulic fracturing, through which the working fluids flow. Because fluid flowing through these systems comes into direct contact with the rock in the subsurface, fluids can leach constituents from the rock and carry them in the fluid to the surface, after which they must be removed for disposal (DiPippo, 2016), or potentially scavenged for critical materials (DOE, 2019). Potential loss of fluid continuity between injection and production wells can also occur, meaning that some fluid may be lost to the surrounding rock.

Although reports of soil and surface water contamination are uncommon near geothermal facilities, some studies have shown that poor water and materials management can lead to both (Balaban, et al., 2017). Others have described pathways to groundwater contamination from operating systems. In one case, Aksoy, et al., (2009) reported that hot geothermal fluids traveled through geologic faults and annular spaces in poorly constructed boreholes and contaminated potable surficial aquifers with heat, arsenic, antimony, and boron, rendering the water unusable for drinking or irrigation. Jiang, et al., (2018) also identified arsenic and other constituents in geothermal fluids in Tengchong, China, concluding that they most likely were the source of contamination of surface water and shallow groundwater. These cases highlight the importance of proper well construction and active management of geochemical reactions between fluids and well construction materials. Construction of monitoring wells to detect potential groundwater contamination near Open to Reservoir Systems is also prudent.

Engineered Geothermal and Next Generation Geothermal Systems interact with the subsurface far below the water tables and aquifers used for drinking water and in visible, natural hot springs. Subsurface engineering, in the form of horizontal laterals, has increased in length and now approaches 10,000 feet (1.9 miles or three kilometers) or longer in the oil and gas context. Conventional Hydrothermal Systems have rigorous water resource management protocols so the risk of water contamination and spring water depletion are unfounded or nonexistent.

2. Closed to Reservoir Systems

AGS/Closed Loop Geothermal Systems ("AGS"), as discussed in depth in *Chapter 1, Geothermal and Electricity Production* of this Report, maintain separation (in some designs, to a greater or lesser degree) between the Working Fluid and the reservoir, and are therefore referred to as Closed to Reservoir. Fluids are introduced into the subsurface through vertical injection boreholes, flow through well pipes of assorted designs, and exit through production wells. AGS are most commonly used in shallow Direct Use Geothermal Systems. System designs are codified by state environmental regulatory agencies. Working Fluids are nontoxic, or they contain low-toxicity additives to enhance volumetric heat capacity of the fluid (hence, efficiency of the system). Working Fluids, available in many locations and commonly glycol based, must be carefully chosen to avoid corrosion, scaling, and/or biological buildup in pipes and other system components, all of which reduce efficiency and operational life.

AGS are increasingly proposed as utility scale systems with capacities in the tens of megawatts per borehole. These systems are being proposed and/or demonstrated using several designs, from "pipe-in-pipe" configurations within a single borehole, to U-shaped loops that are connected by vertical boreholes several kilometers apart from one another. Designs such as proposed by geothermal startup Eavor (Eavor, 2021), uses a combination of horizontally drilled laterals connected to one to two (or more) sealed vertical wells to create a subsurface radiator pattern, in which colder (denser) fluids are introduced into the injection well that displace hotter (less dense) fluids from the production well, after which heat is harvested from the fluid and reinjected (Fallah, et al., 2021; Yuan, et al., 2021). This thermosiphon approach theoretically avoids the parasitic loads that occur in Conventional Geothermal Systems and some EGS concepts. Figure 10.4 shows the subsurface configuration of an AGS.

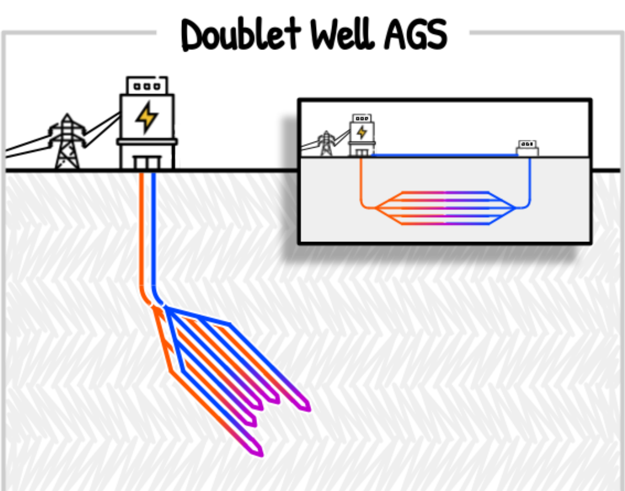

Figure 10.4. Example of a "Closed to Reservoir" AGS design. *Source: Adapted from Eavor, 2021.*

Whereas concepts like proposed in Figure 10.4 have a number of advantages, the system nevertheless relies on effective connection of drill pipes while in the borehole, requiring long term operations without deterioration of connecting points that might be sources of leakage of Working Fluid into the reservoir. Advances in completion and casing technologies and methodologies may be required to assure that systems such as these operate in a truly closed loop manner, without leakage into the surrounding reservoir. Monitoring studies would provide confidence in the operational integrity of this emerging technology. As discussed in Chapter 1, Geothermal and Electricity Production of this Report, engineered Working Fluids for use in AGS are being studied extensively, mostly through numerical models or plot scale demonstration projects (Fallah, et al., 2021; Amaya, et al., 2020; Hu, et al., 2020; Oldenburg, et al., 2016).

Some of the emerging "Geothermal Anywhere" concepts described in this Report, such as some Hybrid Geothermal Systems, combine open and closed to reservoir concepts, but a majority of these designs report to maintain separation between the Working Fluid and reservoir. Recently, for example, Fallah, et al. (2021) described a U-shaped design with an open-hole, horizontal borehole connecting two vertically cased boreholes. Their modeled design maintained positive pressure through the horizontal section, thus avoiding potential mixing of formation water with the Working Fluid. However, this team did not address the potential loss of Working Fluids into the formation, an aspect of the design that deserves more attention.

3. Potential for Using Produced Water

Water that is co-produced with oil and gas is a potential source of Working Fluids for geothermal, depending on fluid chemistry, need, and access to alternative sources. Two ongoing challenges when using produced water for geothermal (or any other beneficial use) are (1) the spatiotemporal variability of produced water quality, especially for constituents at concentrations that could lead to corrosion, scaling, bioclogging, etc., and (2) the availability of sufficient quantities of water where and when it is needed.

Scanlon, et al., (2020a, 2020b) assessed and compared the quantity and quality of produced water across ten U.S. oil and gas, and five coalbed methane ("CBM") plays, considering different beneficial uses and requirements for quality (e.g., when irrigating crops for human consumption). They found median concentrations varying from 9,000 to 200,000 milligrams per liter total dissolved solids ("TDS") in the oil and gas plays, and from 1,000 to 10,000 milligrams per liter in the CBM plays. Depending on fluid chemistry needed for the geothermal technology in question, water with this level of TDS may or may not be suitable without primary or secondary treatment to remove salts, stabilize pH, etc. If treatment is needed, as Scanlon, et al., (2020a) pointed out, the volume of produced water available could drop by 50 percent, and the concentrate would still require handling and disposal. The decision about using produced water for a geothermal system thus needs to be based on availability of other suitable sources of water, and the economics of treating the water onsite, versus purchasing higher quality water elsewhere, as well as other operational factors.

B. Other Considerations

1. Solid-Waste Generation and Fluid Management

Two methods of fluid management can be used to address dissolved constituents in return Working Fluid in geothermal systems. One is a flash crystallizer that permanently removes dissolved constituents for subsequent disposal, and the other is pH modification that keeps constituents in dissolved phases for reinjection (DiPippo, 2016). Depending on the concentration, mineral recovery in the returned geofluids could be economically favorable.

For example, the country's recent pivot toward renewable electricity generation using wind and solar, as well as the need for substantial electricity storage in batteries, has added urgency to finding sustainable sources of rare earth elements ("REE") and critical materials for manufacturing and technology development. Research that matches the presence of REEs and favorable sites for geothermal has been reported for some time (Fowler, et al., 2019; Williams-Jones, et al., 2012; Lottermoser, 1992), and we can expect those activities to continue, especially in geothermal technologies in which fluids contact host rock directly.

Although reinjection of used Working Fluids is the conventional geothermal industry standard (for environmental and reservoir management reasons), if for some reason Working Fluids were disposed of at the surface, the unused heat in the return flow would be a source of waste, and a potential source of thermal contamination. Surface disposal of geothermal wastewater containing heat and dissolved constituents could also lead to downward movement of contaminants (Kjaran, et al., 1989), which would require site-specific analyses to assess possible impacts.

2. Surface Emissions and Monitoring

With regard to any Open to Reservoir geothermal design, Bayer, et al., (2013) noted potential atmospheric emissions, especially from flash or dry steam plants, including waste heat through steam, and non-condensable gasses ("NCG") such as H2S, CO2 and methane. The waste heat, for example, could be an issue for surrounding biota or residents, and release of NCGs could, of course, offset the value of replacing fossil fuel generating plants with geothermal.

Bayer, et al., (2013) cited Bloomfield, et al., (2003), who in turn cited Goddard and Goddard, (1990). The data provenance in these references, published by the Geothermal Research Council, are unknown, but they provide an early discussion on the potential release of NCGs and their risk to the emission benefits of geothermal power. For example, Dumanoglu, (2020) examined this topic using both passive and continuous monitoring, primarily for H2S, at a 50 megawatt power plant near Aydin and Manisa, Turkey. They found 14 day average concentrations between 51.4 and 52.5 micrograms per cubic meter to be below World Health Organization ("WHO") criteria of 100 micrograms per cubic meter, although over the short term, concentrations peaked above regulatory limits several times, with concentrations exceeding the odor threshold many times.

Peralta, et al., (2013) also monitored meteorological conditions around a (then) 720 megawatt power plant in Cerro Prieto, Mexico, one of the largest in the world, generating nearly five terawatt hours in 2003. Their systems, deployed across five monitoring locations in the field, collected significant micrometeorological and air quality data, with constituents that included gasses such as H2S, CO2, SOX, and NOX, (hydrogen sulfide, carbon dioxide, sulfur, and nitrogen oxides). They found average measured H2S concentrations of between 1.5 and 45 micrograms per cubic meter, depending on location and time of day of sampling from variability of the boundary layer around the plant influencing downwind concentrations.

Parisi, et al., (2019) conducted a life-cycle assessment (a comprehensive environmental impact study) on 34 operational power plants in the area of Tuscany, Italy. Air quality data in their study were collected by the regional environmental regulatory agency. NCGs collected from the condenser unit were analyzed for NCGs (CO2, CH4 (methane), NH3 (ammonia), H2S), as well as gaseous mercury, and numerous other trace metals were also monitored. These data were then expressed in units of grams per megawatt hour of electricity generation for each constituent.

Considering concentrations alone (outside of typical life cycle assessment) and assuming a plant capacity of 50 megawatts (arbitrary) operating 24/7 for one year (438 gigawatt hours per year), H2S release could range from 404.7 to 709.6 tons per year. Abatement infrastructure could substantially reduce these emissions, feed them back into the injection stream, and further mitigate the potential for release into the environment or into nearby communities.

To restate a key point, in Texas, particularly with the development of Closed to Reservoir geothermal systems as opposed to Conventional Hydrothermal Systems, which are the subject of the case studies above, the concerns outlined above may be substantially mitigated, or even eliminated with some next generation geothermal concepts. Closed to Reservoir systems, such as AGS and some Hybrid Geothermal Systems, separate formation fluids and Working Fluids. These systems are designed to just produce heat, without producing unwanted contaminants and gasses from the subsurface. Emissions during operations should therefore be kept to a minimum, or eliminated altogether.

V. Comparing Surface Impacts with Renewable and Fossil Energy

In this final Section, we will consider surface impacts of geothermal development, and compare it with other energy sources, including both renewable and fossil based sources. Topics that will be considered include surface footprint, traffic, and noise levels associated with the development and operation of plants.

A. Surface Footprint

All energy systems, whether they generate molecules or electrons, require construction of infrastructure, such as wells, turbines, pipelines, power plants, transmission lines, etc. Surface space to host production facilities is required across the board, whatever the energy source may be. Fortunately, given the design, deployment, and use of many different utility scale energy systems for over a century, we have a thorough understanding of the surface footprints that (at least historically) have been required for these systems.

Crucially also, innovation has reduced surface footprints as systems have evolved with time, experience, and an acknowledgment of the importance of land conservation as an ancillary goal. In Figure 10.5, the surface footprint of all major sources of energy is compared (Lovering, et al., 2022). Of these energy sources, including renewables like wind and solar, geothermal takes up the least amount of space on the surface, per unit of electricity production.

1. Oil and Gas

In research relevant to geothermal development, Pierre, et al., (2017; 2020) reported on a time series of land surface alteration from drilling pads (and, by extrapolation, from pipeline construction) for the Eagle Ford and Permian Basin areas of Texas, respectively. They showed a spectrum of current land alteration scenarios that depended on degree of drilling and number of multi-well drilling pads, though restoration following on-site activities have mitigated some of these impacts. Because geothermal development in Texas is likely to follow the paradigm of drilling used in oil and gas, also known as "pad drilling," this research gives perspective of what large-scale geothermal deployment might look like in Texas.

Beginning in the early 2000's, unconventional (shale and tight rock) plays became the dominant source of fossil energy exploration, leading to a larger per well support area needed for each well, particularly in the size of the drill pad; 1.5 hectares and up, much larger than typical well pads (Johnson, 2010). Because of the need for tight lateral spacing and much smaller drainage volume per well, the spacing of well pads have become closer, creating denser landscape alteration patterns (McClung & Moran, 2018).

Note that, although the number of geothermal plants in the U.S. is relatively small, and in Texas there are currently zero, experience that could be transferred from the oil and gas industry is significant, especially with respect to land use needs. Both industries require drilling pads for hosting boreholes, both benefit from horizontal drilling and stimulation (in the case of EGS), and both connect wellheads to infrastructure that captures an energy product.

2. Wind and Solar

Renewable energy generating facilities, specifically in the form of wind and solar installations, also impact landscapes in diverse ways. Land alteration from wind energy in particular differs from other energy sources, not only because the tower, turbine, and blades are above ground, but also because the blades have a wingspan that far exceeds its surface footprint. Different researchers approach the total (direct and indirect) impact of onshore wind energy differently. One well cited study (Denholm, et al., 2009) evaluated 172 existing or proposed (at the time) projects, focusing more on land area occupied and less on intensity of the impact. These researchers illustrated nuances of the direct impact of turbine pads, roadways, support areas, etc., and a more vague, more subjective use of indirect land use that is included in total area, including spaces between turbines or the blades themselves (depending on blade length).

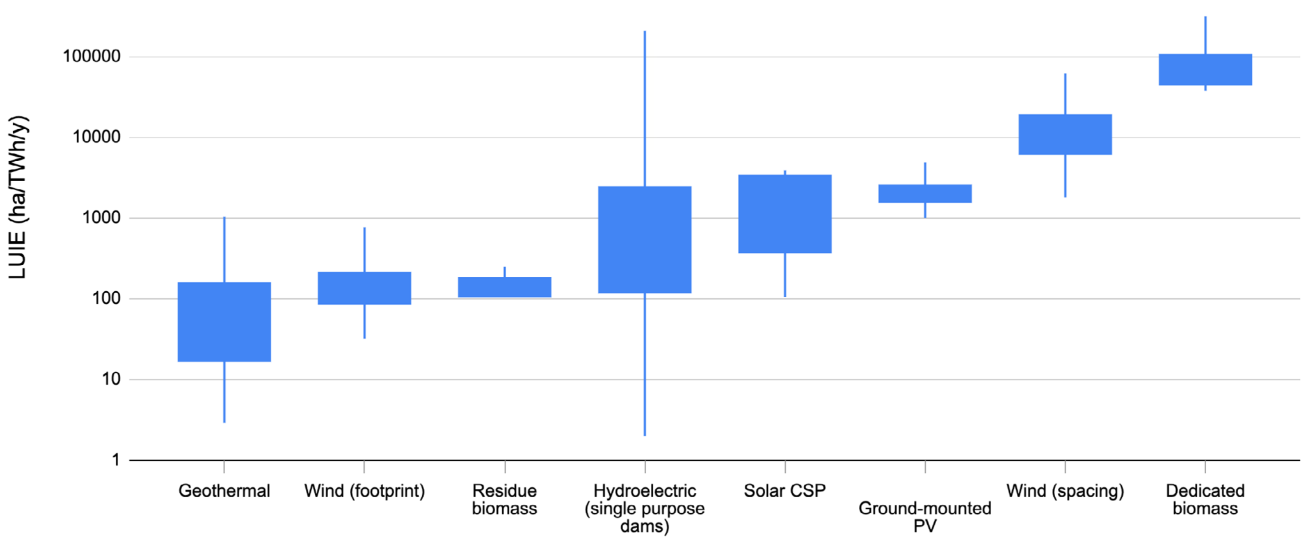

Figure 10.5. Comparison of land use intensities between different renewable energy systems. Notes: Wind- refers to wind towers only and Wind+ includes the land in between the towers. Geothermal refers to geothermal energy generation including the generation facility and onsite production wells. *Source: Adapted from Lovering, et al. (2022).*

Land alteration for wind in particular is sometimes vaguely defined, because the land between turbines, still within the facility boundary, often remains in use (e.g., for agriculture), hence the use of two different land use intensity values for wind; one for just the land use for the tower (Wind-), and the other that includes the space between the towers (Wind+). Impacts to habitats, avian species, and other site operations (e.g., other infrastructure) are often site specific and would require specific analyses, sometimes down to a species level, or ecosystem service approaches (e.g., Stanford University's Natural Capital Project). The potential impacts on viewsheds, soundsheds, and local communities in the form of externalities like shadow flicker could also come into play, again, depending on site-specific factors.

Land alteration from solar energy infrastructure is easier to quantify than from wind energy because photovoltaic panels and related hardware are closer to the ground, often one to two meters above the surface. Moreover, the infrastructure is often more densely packed, removing some of the ambiguities of indirect impacts, as is the case for turbines. As reported by Lovering, et al., (2022), the land use intensity for ground mounted solar photovoltaic panels is over 40 times higher than for geothermal.

3. Geothermal

In general across all technologies, a single representative value of land use for all of geothermal facilities and designs is difficult to determine. Estimates of geothermal direct land use range from approximately 350 megawatts per square kilometer (or 0.70 acres per megawatt) (Kagel, et al., 2007) to approximately 830 megawatts per square kilometer (or 0.30 acres per megawatt) (DiPippo, 2016), with a midrange estimate ranging from 500 megawatts per square kilometer (or 0.49 acres per megawatt) (DOE & EPRI, 1997) to approximately 1,000 megawatts per square kilometer (0.97 acres per megawatt (Lovering, et al., 2022). DiPippo (2016) also noted that a geothermal-flash or binary plant requires two percent of the land area required for a solar photovoltaic plant located in the best insolation area in the United States, when compared side-by-side in capacity.

Factors relevant to geothermal land needs are, to name a few, the quality and lateral extent of the reservoir, the efficiency factor of the plant, and the number and interspatial distances between drilling pads and pipelines needed for moving fluids.

Bayer, et al., (2013) reported the land footprint to require around 0.85 square kilometers per 50 megawatt plant, an area that includes well pads, cooling towers, roadways, transmission lines, etc.

A key factor in total land use is the potential need to store wastewater brines, particularly in the case of conventional geothermal systems. Though this is less likely to be relevant in Texas as next generation concepts are deployed, if necessary, these vessels could increase land use by 75 percent.

Once drilling is complete, next generation geothermal systems (AGS, EGS, etc.) offer the potential for smaller footprints relative to hydrothermal systems in two ways. First, these systems are anticipated to be in the low tens of megawatts per installation, with density of installations kept low for geophysical reasons. Generation will therefore most likely be located immediately adjacent to the drilling pad, minimizing the footprint created when above or below ground pipelines are needed to move fuel. Second, the emerging supercritical CO_2 based turbines have demonstrated an order of magnitude or greater reduction in size when compared to current state-of-the-art Organic Rankine Cycle turbines, thus allowing for a small post drilling footprint. These new technologies may allow next generation geothermal plant turbomachinery components for a several megawatt pilot plant to fit within the size of a tractor trailer container (Sage Geosystems, 2022).

That said, currently, even next generation plant concepts will require fluid cooling/condensing, which is a contributor to the surface footprint of geothermal developments. Further, the Texas climate in summer months poses a challenge for traditional air cooling technologies, and may increase the square footage requirement of cooling systems to maintain performance efficiency. This is an area where both innovation and piloting is needed to further understand the impact that geothermal plant cooling/condensing requirements will have on the footprint of new future developments in Texas.

4. **Other Land Use Considerations**

The impact of transmission lines constitutes the largest source of the range in land use estimates reported at around 0.215 to 1.485 square kilometers per 30 to 50 megawatt plant. This is equivalent to about nine acres per megawatt, assuming a 40 megawatt capacity, which is a footprint similar to that of utility-scale solar.

Land alteration should be considered through direct and indirect lenses, since ecosystem impacts extend away from direct alteration. Many authors have used a buffer of approximately 90 to 100 meters around directly altered areas (Pierre, et al., 2020; Drohan, et al., 2012; Johnson, 2010; Jordaan, et al., 2009) as a measure. Therefore, for those geothermal well fields that require a large number of wells, especially if the wells are spaced more than 328 feet (100 meters) apart, the sum of direct and indirect alteration could become sizable, even if the power plant itself is relatively compact.

To further reduce an effective land footprint and potential land fragmentation issues, site remediation and conservation practices should be considered at the initial stages of facility design and then implemented as soon as practicable, so that long term impacts are minimized. Measurable reductions in regional land alteration were noted in the Eagle Ford Shale play (Pierre, et al., 2015), one of the largest in Texas, after consistent land reclamation practices were implemented.

Disturbances from removal of vegetation can increase dust emission potential, which can be a respiratory hazard in humans, especially for utility scale solar energy, with blading and grading for the panels, frames, and roads. Dust erosion, although potentially significant in long-term solar panel efficiency, is probably not an issue in the geothermal context.

Figure 10.6. The cooling towers of the Ormat Tungsten Mountain hydrothermal plant, located in Nevada. *Photo Credit: Ormat Technologies.*

B. Road Traffic

Few, if any, studies have been published in open literature on traffic issues related to geothermal development, though, exploration, well drilling, and infrastructure development activities would be similar to oil and gas development. The Academy of Medicine, Engineering and Science of Texas ("TAMEST") recently summarized changes in truck traffic and truckloads associated with unconventional oil and gas exploration. In chapter seven (Transportation) of the TAMEST report (2017), the authors noted that increased truck traffic resulting from initial exploration, pad drilling and development, site maintenance, and other site activities can significantly increase traffic through communities, representing a significant negative externality to community members during the development phase of a project.

Moreover, Quiroga, et al., (2012) reported on study results showing the increased number of truckloads traveling in rural areas of Texas, both empty and full load vehicles, can impact roadways. These impacts are particularly noteworthy on rural roads, which often are not designed to carry heavy loads. Quiroga, et al., (2012) showed, for example, that a 25 percent increase in vehicle weight from 80,000 to 100,000 pounds would result in an increased pavement impact of 140 percent. An obvious trade off seems to exist between reducing the number of trucks on the road, which benefits local residents in a number of ways, against the heavier load of each truck imparting a larger impact on road quality. Quiroga, et al., (2016) also estimated a total number of truckloads, normalized to a single-axle vehicle of equivalent weight (e.g.,18,000 pounds) and reported a range of per well truck trips from 5,513 in the Barnett Shale to 11,211 in the Permian Basin.

Although operations for geothermal projects will differ in some ways from those of an unconventional hydrocarbon well field, impacts related to fluid management and disposal, truck traffic and road impact/damage need to be accounted for in initial planning and impact mitigation activities for projects under consideration in areas where populations may be impacted.

C. Noise levels

Geothermal plants in general terms are likely to be no different than any other power or industrial facility of equivalent size and scale. Noise levels are elevated during road construction, excavation and drilling at well sites, and well testing. This quality of life concern, which has been noted in oil and gas exploration and development (Anderson & Theodori, 2009), is typical of other well drilling activity, which is of high intensity, and short duration. Noise from drill sites can be mitigated through the use of sound walls or barriers, a relatively standardized practice.

After the wells have been constructed and plants begin normal operations, components of the plant contribute to elevated ambient noise, including compressors, generators, motors, pumps, and fans. Noise also occurs during abnormal operations, such as when the plant is forced offline, or when/if emergencies occur that require adoption of measures that are not a typical part of standard operating procedures.

Gupta and Roy (2007) listed a number of environmental concerns related to geothermal development, including noise pollution from fluid handling, especially for venting or fluid release to manage pressure. At high noise levels due to waste fluid release, they recommended subwater release (e.g., into a storage pond). For low noise management, they recommended the use of silencers, which are vertically oriented pipes that increase in diameter with height. Other options that co-manage water and associated noise are also described.

As noted above, it is important to note that these observations have been made in the context of conventional hydrothermal geothermal development, which will likely be a small part of Texas' geothermal development. With the development of next generation geothermal concepts in Texas, many of the environmental externalities that have been observed to be associated with conventional hydrothermal geothermal operations are not expected to be of concern. This is an area where further inquiry is needed, as the first plants piloting next generation concepts come online in the coming years.

VI. Conclusion

While this Chapter took a hard look at potential negative environmental externalities associated with geothermal developments, when compared with other renewable sources of energy, geothermal shines in the realm of environmental impact, having low lifecycle carbon emissions, the smallest surface footprint, and low potential for water contamination. From a broad global environmental standpoint, a low or no carbon, baseload, small footprint energy source, without significant waste streams, has substantial upsides and value as the world seeks to decarbonize its electricity generating systems. Even so, all energy sources have some environmental impact, and geothermal is not an exception.

Many environmental considerations discussed herein and related to geothermal, like high water use, the potential for emissions to ground surface, and the potential for induced seismicity, are most relevant to Conventional Hydrothermal Systems ("CHS"), and potentially also to Traditional EGS. These potential impacts may be significantly mitigated, or simply not present, in next generation geothermal concepts such as AGS, and some Hybrid Geothermal Concepts. For example, next generation AGS/Closed Loop concepts may not involve induced seismicity risk, which is a concern in CHS and Traditional EGS geothermal contexts. Further, the use of engineered Working Fluids, like supercritical CO2 instead of water may mitigate high water use, which is also implicated by CHS and Traditional EGS.

Nonetheless, a majority of these next generation geothermal concepts have not been sufficiently field deployed to allow for data collection and analysis of the environmental impact in real world deployments. While this Chapter represents a step forward in this area of analysis, these areas of fast moving innovation will require further analysis and study as new data from field trials of next generation concepts becomes available over the coming years.

Conflict of Interest Disclosure

Michael H. Young serves as a Senior Research Scientist at the Bureau of Economic Geology, Jackson School of Geosciences, the University of Texas at Austin, and is compensated for this work. His main areas of research for over 35 years have been in the broad area of environmental geosciences, water resources, and landscape scale processes, particularly applied to understanding impacts from energy development. Outside of these roles, Michel Young certifies that he has no affiliations, including board memberships, stock ownership and/or equity interest, in any organization or entity with a financial interest in the contents of this manuscript, and has no personal or familial relationship with anyone having such an affiliation or financial interest.

Ken Wisian serves as an Associate Director of The Bureau of Economic Geology, Jackson School of Geoscience at the University of Texas at Austin, and is compensated for this work. His main area of research for 30 plus years in geothermal systems. Outside of this role, Ken Wisian certifies that he has no affiliations, including board memberships, stock ownership and/or equity interest, in any organization or entity with a financial interest in the contents of this manuscript, and has no personal or familial relationship with anyone having such an affiliation or financial interest.

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