Geothermal Energy and Greenhouse Gas Emissions

November 2012

Two new geothermal power plants in California: EnergySource's John L. Featherstone Plant (top) and Ormat's North Brawley Plant.

GEOTHERMAL ENERGY ASSOCIATION

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By Alison Holm, Dan Jennejohn, and Leslie Blodgett, GEA

1. Introduction

Geothermal energy is an environmentally friendly, renewable, and sustainable source of electricity. It is well positioned to play an important role in mitigating global climate change, increasing national energy security, and safeguarding public health. Emissions rates associated with geothermal power plants are much lower than emissions from coal or natural gas-fired power plants.[1] Geothermal plants emit about 5% of the carbon dioxide, 1% of the sulfur dioxide, and less than 1% of the nitrous oxide emitted by a coal-fired plant of equal size, and certain types of geothermal plants produce near-zero emissions.[2]

Some types of geothermal power plants release gases into the atmosphere during the power conversion process due to the presence of naturally occurring dissolved gases contained in most geothermal systems.[3] This does not involve direct combustion of the primary energy resource, and it is difficult to differentiate from naturally emitted gases from the hydrothermal system that would be present without human interaction. It remains a challenging task to quantitatively determine the true emissions footprint of geothermal energy development, due in large part to the inherent existence of these naturally emitted gases, including greenhouse gases (GHG), and inconsistent monitoring from production facilities required by states for these purposes.

As the resource is developed and used for power production, both the types of GHGs emitted and the emissions rates themselves show wide variation among geothermal resource sites in the United States. The unique resource chemistry associated with individual geothermal sites, including the resource temperature and rock type in the reservoir, and a variety of other factors, including the type of geothermal power plant built (dry steam, flash, binary), affect the amount of GHGs emitted into the air.

Little work has been done in the area of quantifying GHG emissions and differentiating between natural geothermal emissions and those attributable to geothermal power plants, and the site-to-site variance adds further difficulty to an attempt to characterize emissions for the geothermal industry at large. As this paper explores, though, it is clear that geothermal emissions rates are well below those of traditional fossil-fuel plants, and this is important when considering how to minimize the greenhouse gas emissions of the electricity producing sector.

2. Greenhouse Gases, Noncondensable Gases, and Natural Geothermal Emissions

Greenhouse gases are those that heat the atmosphere through their interaction with incoming or reflected solar radiation. The principal greenhouse gases that human activities release to the atmosphere are carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and fluorinated hydrocarbon gases. Some of these, such as carbon dioxide, are emitted through both natural processes and human actions. Others, such as fluorinated gases, are created and emitted only though human activities.

In geothermal resources, the noncondensable gases – gases that are not easily converted to liquid form via a cooling mechanism – include carbon dioxide, with smaller amounts of ammonia, nitrogen, methane, hydrogen sulfide, and hydrogen.[4] The amount and relative proportion of noncondensable gas components can vary substantially from one geothermal resource to another. Bloomfield and Moore (1999) worked with plant operators to collect data on the mass ratio of steam to total noncondensable gas. An example of the data published in the paper is shown in Table 1.[5]

Table 1. Example of Proportion of Noncondensable Gases at a Geothermal Resource

Noncondensable Gas Component	Dry Gas % by Volume
Carbon Dioxide	97.8
Hydrogen Sulfide	1.2
Methane	0.5
Ammonia	0.05
Total	**100**

Source: Bloomfield and Moore (1999)

Together the noncondensable gases typically make up less than 5 percent by weight. The measurement of these gases in geothermal fluids is highly important during preliminary well testing for power plant design and regulatory concerns.[6]

Because geothermal systems naturally contain these gases, they also naturally vent them to the atmosphere through diffusive gas discharges from areas of natural leakage, including hot springs, fumaroles, geysers, hot pools, and mud pots. These natural discharges have taken place throughout the history of the Earth and continue today independent of geothermal power production. Carbon dioxide is the most widely emitted gas because geothermal systems tend to be found in areas with large fluxes of carbon dioxide. Methane is the second most common greenhouse gas emitted naturally from geothermal systems, but those emissions are minimal.

Because geothermal systems are natural sources of greenhouse gases, isolating the emissions attributable to human activities requires more than a simple measurement of emissions from a particular site. Understanding how natural emissions are altered by industrial utilization would require a baseline determination prior to power development since GHGs are present in both producing and non-producing geothermal systems. If power production has already begun, baseline information would have to be collected both before and after new capacity is brought into service, but this data can be difficult to obtain.[7] Such baseline information is usually unavailable in practice unless the area has been the subject of an academic research program or the measurements have been required for regulatory reasons. Further complicating this issue is that even if baseline information is obtained, it is difficult to make generalizations from one site to another because of the site-specific character of each field's geology and geochemical characteristics.[8] Additionally, standardized methods for measuring natural emissions are not currently available.

3. Geothermal Power Plants and GHG Emissions: Resource Chemistry and Power Plant Type

Although geothermal power plant emissions arise primarily from existing geothermal resource gases and not from the power generation process itself, research shows that the specific characteristics of the resource, as well as whether the power plant is open versus closed (binary), influences the rate at which those gases are released.[9] Industrial utilization of a geothermal field causes the natural emissions to go from being concentrated in the field to being concentrated in the power plant.[10] Therefore, the technology of the geothermal power plant can also influence the rate at which the gases will be released. Also, the emissions from the power plant may decrease over time as the production of fluid serves to degas the natural reservoir.

Geothermal power plants on-line today fall into one of three categories of power cycles[11]: dry-steam, flash-steam, or binary; of which only the first two are likely to emit any measurable amounts of GHGs. Noncondensable gas content is a key factor in designing turbines, condensers, gas removal systems, and hydrogen sulfide abatement systems for geothermal power plants. In dry and flash steam plants, noncondensable gases are separated from the steam turbine exhaust in the plant condenser and are either discharged to the atmosphere (air, carbon dioxide, and other nontoxic components) or removed by an abatement system (hydrogen sulfide is usually converted to solid elemental sulfur).[12] These types of plants emit about 5% of the carbon dioxide, 1% of the sulfur dioxide, and less than 1% of the nitrous oxide emitted by a coal-fired plant of equal size.[13] Binary power plants retain noncondensable gases in a closed loop system while the geothermal brine is being utilized for electricity production. Eventually, the geothermal fluid and contained gases are injected back into the reservoir. The result is near-zero emissions as the noncondensable gases are never released to the atmosphere.

As with natural geothermal emissions, the most commonly released gas from geothermal power plants is carbon dioxide. Small amounts of ammonia, methane, hydrogen, nitrogen, argon, and hydrogen sulfide can also be emitted.[14] The amount of gases that are present in the geothermal fluid and which might be emitted depends on a variety of factors. The main factor are the resource fluid chemistry, water phase (dry steam or liquid), and temperature, but the type of power plant (flash, dry steam, binary, or combined cycle) and the plant characteristics (efficiency and hydrogen sulfide or other gas abatement systems) also influence emission levels.[15]

As previously discussed, a fundamental aspect affecting geothermal emissions appears to be the natural chemistry unique to the specific hydrothermal resource. The reservoir's temperature, pressure, fluid chemistry, including noncondensable gas content, all impact the type of power plant, abatement, and cooling system design appropriate for that site. Power plant design, in turn, also affects the amount of gaseous emissions released. Geothermal power plants that utilize an open system, such as steam and flash power plants, generally vent emissions to the atmosphere, although their emissions are usually minimal. Geothermal power plants that use a closed system, such as binary-cycle power plants, retain the noncondensable gases in the geothermal fluid and inject them back to the geothermal reservoir, emitting near-zero emissions because the geothermal resource is not exposed to the atmosphere.[16] Since binary-cycle plants can utilize lower temperature resources (below 400°F), which are much more prevalent throughout the U.S., it is expected that binary plants will be a staple of future industry growth and have been the primary designs constructed in recent years.[17] It should be noted that all geothermal plants have to meet various federal, state, and local environmental standards and regulations, although emissions are not routinely measured below a certain threshold, and emissions from geothermal plants typically fall below this threshold.

4. Relationship Between Natural and Anthropogenic Emissions at Geothermal Power Plants

Distinguishing between natural and anthropogenic emissions associated with geothermal resource development is difficult because of the dispersed nature of natural emissions. Emissions are also a direct result of the natural resource chemistry at the site and cannot be generalized for geothermal resources due to the natural site-to-site variation. None (or very little) of the CO_2 is anthropogenic, or "man-made". However, geothermal development can impact the rate at which natural GHGs are released. For example, the CO_2 that is emitted as a result of development was originally dissolved in the reservoir fluids. Under natural conditions this CO_2 gradually seeps out into the biosphere and is in turn very slowly replenished through continued generation in the rocks within and below the reservoir. Constructing a geothermal project can disturb this state of natural equilibrium, and may cause the CO_2 to escape more rapidly at first, resulting in higher rates of gas flow into the atmosphere than from the undisturbed system. Eventually, however, as the CO_2-depleted waste brine is reinjected back into the reservoir, the concentration of dissolved CO_2 in the reservoir will tend to drop below natural levels, resulting in a decline in surface emissions. After the project is abandoned, a state of equilibrium will eventually become re-established. Over time-scales of millennia, the net human effect may be near zero, with enhanced CO_2 discharges at early times followed by a long period of relatively low gas output.[18]

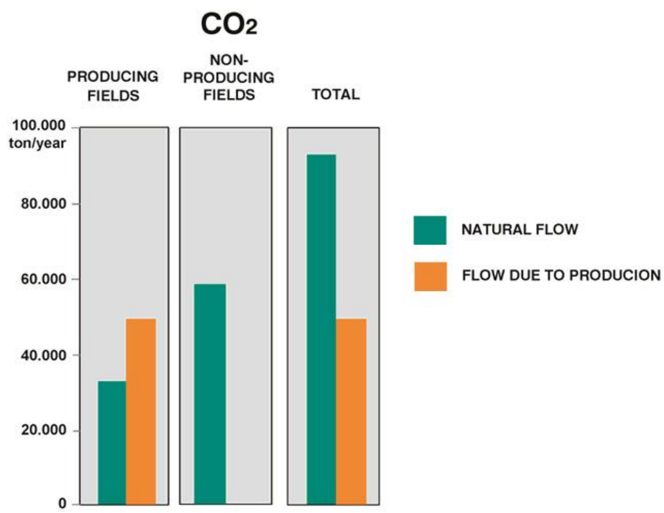
Injection, routinely implemented at geothermal plants for sustainability, has also been shown to reduce the carbon dioxide released from some geothermal power plants. Injection of treated domestic waste water, as at The Geysers in California, also results in a drop in the amount of noncondensable gases produced. For example, CO_2 emissions from the Dixie Valley geothermal plant in Nevada decreased from 152 lb/MWh of electricity produced in 1988 to 93 lb/MWh in 1992 after injection into the field increased and as the natural system became depleted in non-condensable gases during production.[19] At the Larderello fields in Italy, both natural steam emissions and the associated carbon dioxide outflux have decreased as a result of geothermal power development.[20]

One explanation for this is that geothermal fluid injected back into the reservoir during production is depleted in CO_2, thus depleting the CO_2 concentration of the reservoir. As a result, the reinjected fluid will tend to absorb any deep free carbon dioxide gas from the reservoir into the solution in the liquid phase.[21] Without absorption, the free carbon dioxide might otherwise find its way to the surface with the steam.

Studies conducted at geothermal fields in both Iceland and Italy have revealed this effect. Despite a somewhat nuanced initial relationship between geothermal resource development and associated greenhouse gas emissions at those sites, natural greenhouse gas emissions have consistently been reduced or even negated due to field development.[22] Bertani and Thain (2002) cited the Larderello geothermal field in Italy "as an example of a recorded decrease in the natural release of CO_2" attributable to field development.[23]

One estimate by Ólafur G. Flóvenz, General Director of Iceland GeoSurvey, was that about half of the carbon dioxide emissions from geothermal power plants would be emitted anyway through natural processes.[24] Another estimate from Iceland suggests that natural carbon dioxide emissions from geothermal fields significantly exceed those from power plants, as shown in Figure 1.

Figure 1. CO_2 Emissions from Producing and Nonproducing Fields



Source: Armannsson, Halldor, CO2 emissions from Geothermal Plants (Sept. 2003)[25]

Further studies on power plant emissions and their relationship with natural emissions will be necessary in order to fully understand both the amount of greenhouse gases released from geothermal power plants and how that differs from natural emissions.

5. Current Analysis of Geothermal Emissions

Given the growing set of legal mandates to disclose and reduce greenhouse gas emissions, it is necessary to estimate the extent to which geothermal resource development contributes to total greenhouse gas emissions – and the extent to which geothermal production can offset GHG emissions from traditional power generation. Much of the literature published on the subject of geothermal emissions is decades old and considered unreliable because of the many legal and technical changes that have occurred during this period.

While a comprehensive inventory of emissions data from geothermal power plants in the U.S does not exist, the best currently available data set comes from the California Air Resources Board (CARB), collected through the mandatory GHG emissions reporting required under Assembly Bill 32 (AB32).[26] For emissions data reported to CARB for the 2010 reporting year, the Geothermal Energy Association (GEA) calculates weighted emissions averages based on annual power plant generation data publicly available through the California Energy Commission (CEC).[27] Taken together, these data sets represent the best available empirical look into emissions from geothermal facilities.

However, there are some important disadvantages to employing these data in quantitatively analyzing the current status of geothermal GHG emissions, the primary reason being that power plants emitting less than 2,500 metric tons carbon dioxide equivalent (CO_2e) annually are exempt from reporting GHG emissions to CARB under AB32.[28] Emissions from several California geothermal plants fell below this threshold, and are therefore not represented in CARB's facility emissions database. This reality skews the statewide geothermal emissions rate towards higher emitters. Also, geothermal emissions data from California is very likely not representative of the larger U.S. geothermal industry. For example, the State of Nevada, which has the most installed geothermal capacity of any state other than California, does not routinely collect emissions data, but fragmentary evidence suggests that Nevada projects will have lower greenhouse gas emissions than those presently operating in California. First, around 70 percent of the installed geothermal generating capacity in Nevada consists of binary plants, emitting almost no GHGs, whereas only around 13 percent of California's geothermal generating capacity is binary. Second, as the CO_2 emissions values used in the Dixie Valley, Nevada example (see Section 4) indicate, emissions rates from Nevada fields may very well be lower than those from comparable plants in California.

Furthermore, many of California's geothermal resources are highly unusual from a geo-hydrological standpoint and are likely unique in the U.S. The Imperial Valley fields, for example, host geothermal fluids that are very hot and are also much more saline than those found in other U.S. geothermal reservoirs. Future growth of the geothermal industry is likely to progress eastward from the large, high-temperature systems in California containing relatively higher concentrations of noncondensable gases into the Great Basin (Nevada, Idaho, Utah, Arizona, New Mexico, etc.), where high levels of dissolved CO_2 in the subsurface geothermal fluids are less likely to be encountered. The lower reservoir temperatures in these newly developing areas will also encourage the utilization of newer binary technology, and binary geothermal plants have essentially zero GHG emissions.[29] It is reasonably clear that presenting emissions data from existing California projects as representative of both current U.S.-wide geothermal emissions, and of future industry development, will result in pessimistic estimates of geothermal GHG emissions.

Despite these obvious problems with the available data, it remains important to synthesize a baseline understanding of the current status of GHG emissions from geothermal power plants in the U.S., and more comprehensive and representative data sources simply do not exist. In many important ways, the data from California represents the upper limit of industry-wide GHG emissions in the U.S.

6. GHG Emissions from Geothermal Facilities in California

GEA here presents the GHG emissions rate in pounds of CO_2 per megawatt-hour.[30] For the sake of consistency in comparing emissions across technologies, and to more accurately assess GHG emissions rates from geothermal plants presented in other reports, this paper presents carbon dioxide emissions only. CO_2 emissions data were taken from publicly searchable portions of individual geothermal facility reports (which break out emissions by type of GHG emitted) for reporting year 2010 available from CARB's web site.[31] These data, along with 2010 net generation data from the CEC, were used to obtain CO_2 emissions rates per megawatt-hour (MWh) of electricity produced by reporting geothermal facilities using the following procedure:

Step 1: Multiply the CARB-reported CO_2 figure for each facility by 2205 to convert it from metric tons to avoirdupois pounds (lb).

Step 2: Divide "lb CO_2" number obtained in Step 1 by the CEC's number of megawatt-hours generated at that facility.

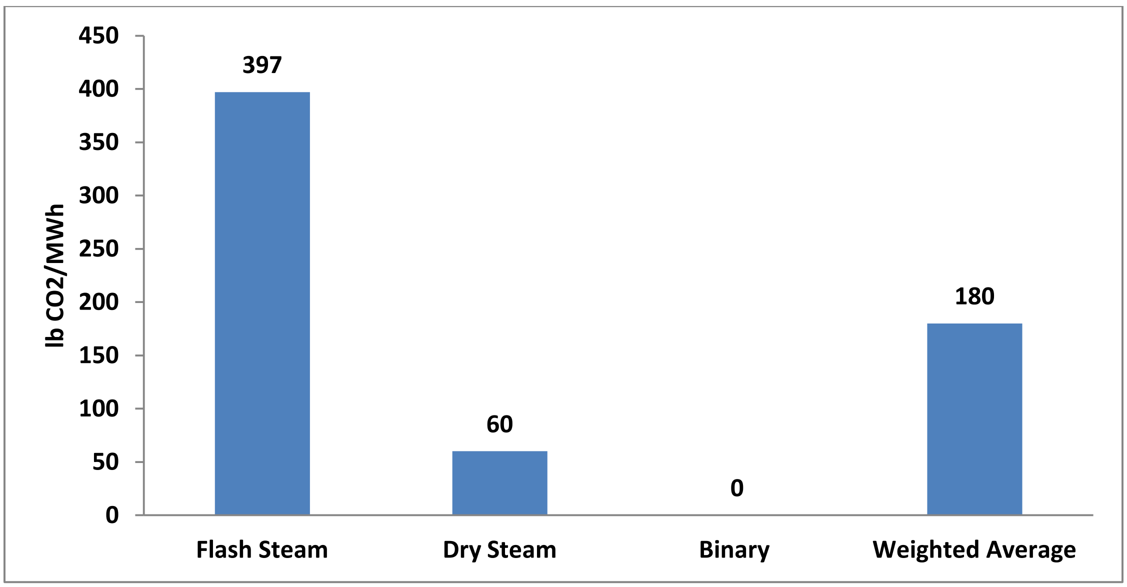
Step 3: The statewide weighted average for reporting geothermal facilities was calculated by adding the lb CO_2 values from all facilities, and dividing that total by the total number of MWh generated at those facilities.

Based on publicly available CARB emissions data and net generation data from CEC, GEA calculated a weighted average emissions rate of approximately 196.85 lb CO_2/MWh from fifteen reporting geothermal facilities in California for reporting year 2010. This emissions value, however, completely excludes non-emitting binary plants, and is therefore neither representative of the U.S. geothermal industry at large, nor the California geothermal industry specifically (nor does it account for temporal variations responsible for different emissions percentages by site depending on length of production). Assuming that the lbCO_2 emissions value from binary plants equals zero, a more representative statewide CO_2 emissions rate from on-line geothermal plants in California is approximately 180 lbCO_2/MWh. It should be noted that an average geothermal emissions rate of 180 lbCO_2/MWh is slightly lower, but still in line with emissions numbers presented in previous studies. Bloomfield et al. (2003), for example, calculated geothermal CO_2 emissions at 200 lbCO_2/MWh, a number which includes zero-emissions from binary plants.[32]

On a per-facility basis, CO_2 emissions from geothermal power plants ranges from 0 lb/MWh to 832.68 lb/MWh (reporting geothermal facilities ranged from 25.02 lb/MWh to 832.68 lb/MWh.) This range reflects the fact that the geothermal resources being tapped for power production are geologically varied.

As noted earlier, the resource chemistry present at a geothermal site yields a different emissions rate and impacts the type of geothermal power plant appropriate to cultivate the site-specific resources. As illustrated in Figure 2 below, based on data reported to CARB, the weighted average CO_2 emissions rate from reporting flash steam plants is 396.52 lbCO_2/MWh. The weighted average from reporting dry steam geothermal plants is 59.83 lbCO_2/MWh. Emissions from non-reporting binary plants are assumed to be zero.

Figure 2. Average 2010 California Geothermal CO_2 Emissions by Generating Technology

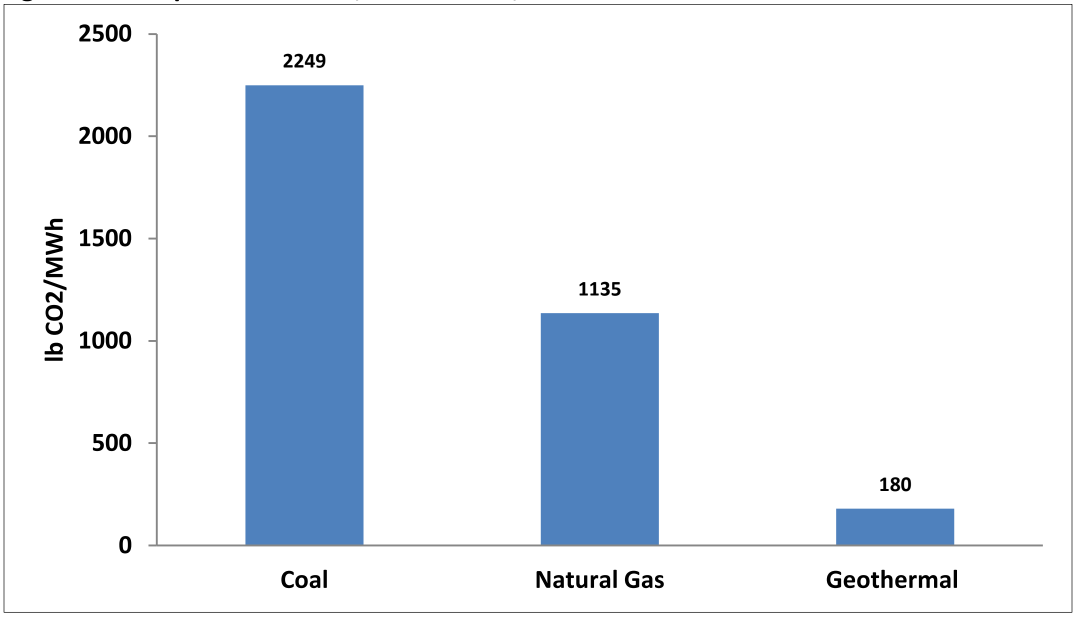


Source: GEA, CARB, CEC

7. Comparison with Coal and Natural Gas

To put geothermal emissions into context, comparable CO_2 emissions data were obtained from the Environmental Protection Agency (EPA) for coal and natural gas power plants. According to the EPA, the average rate of carbon dioxide emissions for coal-fired power plants and natural gas power plants are 2249 lb CO_2/MWh and 1135 lb CO_2/MWh, respectively.[33] The average rate of emissions for a coal-fired power plant and even a natural-gas-fired power plant are significantly higher than that of a geothermal power plant, as shown in Figure 3 below.

Figure 3. Comparison of Coal, Natural Gas, and Geothermal CO_2 Emissions



Source: GEA, CARB, EPA, CEC

As the data demonstrate, compared to fossil fuels, geothermal power plants produce a relatively low amount of greenhouse gases. However, while emissions associated with geothermal power production are significantly lower than direct emissions resulting from coal or natural gas combustion, this comparison still does not provide the most accurate picture of their relative emissions. Geothermal power plants are relatively self-sustained systems contained within the boundaries of the power plant setting. Geothermal power sites encompass the production well field for their fuel, the pipelines to transmit the fuel to the power plant, and the power plant and its associated equipment, such as cooling towers. Emissions reported by a geothermal facility are more appropriately compared with those of a coal or natural gas power plant when the emissions resulting from their complete fuel cycles are noted (including fuel transport). The EPA recognizes that in addition to direct combustion, processes associated with the "production, processing, and transportation" of natural gas and coal generate additional greenhouse gas emissions.[34] Typically these significant fuel cycle emissions aren't accounted for in average CO_2 output cited for coal and natural gas power generation. In order to make comparisons between geothermal power production and coal- and natural-gas-fired power production more realistic, an analysis of complete fuel-cycle emissions associated with fossil fuels should be completed.

8. Gaps in Available Data

Two of the principal problems associated with geothermal emissions reporting are the lack of a consistent reporting method, only reporting above a certain threshold, and that existing methods fail to account for and discriminate between natural and anthropogenic emissions. Problems such as these are not unique to the geothermal industry. This inconsistency leads to limited data sets and difficulties in distinguishing between geothermal resources and/or power plant types.[35] Further exacerbating the problem is the inconsistency in whether or not geothermal emissions are reported, and if they are, how the data are reported and presented.

Some states with greenhouse reporting requirements, such as Nevada, Oregon, and Washington, do not mention geothermal emissions at all. Nevada's requirements state that "units that utilize renewable energy sources are specifically exempted from the reporting requirement."[36] This variation in state regulations and reporting has exacerbated inconsistencies in the data available for geothermal emissions. At the federal level, the EPA has developed new greenhouse gas reporting regulations implemented in December 2009 that requires facilities emitting 25,000+ metric tons of GHGs annually, but does not require reporting of greenhouse gas emissions from geothermal energy.[37]

Although geothermal greenhouse gas emissions are low, additional studies could provide more insight about the relationship between natural and power plant emissions. Understanding this relationship would improve the consistency and accuracy of geothermal emissions reporting. Further, when looking at requirements now being imposed at all levels of government, there are discrepancies about whether geothermal emissions are reported and if so, how they are reported. Most of the methodologies developed for measuring and abating greenhouse gas emissions are related to combustion processes for electricity production. For geothermal power plants, is still has to be determined to what extent any emissions should be classified as anthropogenic.

9. Future Trends and Developing Technology

Other geothermal technologies with the potential to offset carbon dioxide emissions, including enhanced geothermal systems (EGS), are also being developed. According to the Department of Energy, it can be expected that EGS would have minute emissions because these systems will likely utilize closed-loop cycles similar to a binary power plant.[38] For this reason, EGS would emit very little or no carbon dioxide and would therefore offset carbon dioxide emissions. In fact, carbon dioxide mitigation calculations show that utilizing only a small portion of the EGS resource base would significantly lower U.S. greenhouse gases. For example, 100 GW of EGS replacement capacity brought online in 2030 could decrease U.S. carbon dioxide emissions by 21%.[39]

In the aforementioned description, water is used as the heat transmission fluid in EGS, but considerable attention is being paid to the potential of utilizing supercritical carbon dioxide as an EGS working fluid, which would be injected into depleted or dry geothermal systems and used instead of water as a heat transmission fluid.[40] If successful, using carbon dioxide as a working fluid in EGS power plants could result in carbon-dioxide-free or even carbon-negative geothermal power plants.[41] While this technology has yet to be tested, early studies emerging from ongoing research and development projects suggest that supercritical carbon dioxide use may yield various production benefits, including increased rates of heat extraction, to which carbon sequestration could be an "ancillary benefit".[42] Emissions from geothermal plants using carbon dioxide as a working fluid have the potential to be net CO_2 sinks, as these plants may function as carbon sequestration sites with the additional benefit of power production. Carbon sequestration is essentially the process of capturing and storing carbon dioxide at the point of emissions from stationary sources, then permanently storing it deep underground in geologic formations. Technology for this hypothetical sequestration procedure has not been perfected, nor has EGS technology or use of CO_2 as a heat transfer fluid been economically demonstrated. Studies are on-going in each of these areas.

10. Conclusion

Geothermal systems are natural sources of greenhouse gas emissions, and it is difficult to determine what portion of power plant emissions should be considered anthropogenic. Despite this complication, most of the published data on geothermal power plant emissions show that these plants emit little carbon dioxide, minute amounts of methane, and little or no nitrogen oxide. Because of these low emissions, the geothermal power plants also meet the most stringent clean air standards.[43] Lake County, California, located downwind of The Geysers geothermal complex, the largest geothermal field in the world, has met all federal and state ambient air quality standards since the 1980s.

Based upon a survey of the available literature and analysis of new data collected by CARB, it is evident that geothermal emissions are small and vary widely by their resource geology and the type of technology used to produce power. Using the 2010 data submitted to CARB, the production weighted average of carbon dioxide emissions from geothermal power plants in the California was 180 lbsCO_2/MWh. The current U.S. average may be lower and the overall industry average may decline in the future as new technologies are implemented and as the types of geothermal resources outside of California, which appear to produce even lower emissions levels, are developed. In any event, this is a small fraction of the emissions attributable to coal or natural gas power plants.

The fact that geothermal power plants are more environmentally benign than conventional plants should be recognized by government and energy industries moving forward. [44] While geothermal power helps to offset the overall release of carbon dioxide into the atmosphere, it is also offsetting the effects of emissions on people, wildlife, and vegetation. Health dangers that come from fossil fuel emissions of nitrogen, sulfur, and particulate matter (not present in geothermal emissions) include respiratory illness (asthma and bronchitis), heart attack, cancer, and even death. Estimates in 2010 showed the healthcare costs for illness and premature death associated with impacts from coal plants in the U.S. to exceed $100 billion per year.[45]

Quantifying geothermal natural and power plant emissions is a complicated task, greatly impacted by the variability between geothermal sites, but it is clear that replacing fossil fuel electrical generation with geothermal energy will result in a significant net reduction of greenhouse gas emissions and all their associated effects.

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[12] New Zealand Geothermal Association, Wairakei Turbines and Generators. Retrieved from http://www.nzgeothermal.org.nz/geothermal_energy/education/turb-and-gen.asp on March 10, 2009.
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[16] Communications with Dennis Gilles, Calpine, April 17, 2009.
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[21] Communications with John Pritchett, SAIC, April 1, 2009.
[22] Studies at three geothermal powerplants in Iceland found that direct CO_2 discharge to the atmosphere initially increased during the first stages of development as a result of natural steam vents forming above steam cap wells, but that further production led to decreased CO_2 concentration in the steam. Furthermore, data from a study conducted at the Larderello geothermal field in Italy "concluded that all gas discharge resulting from power production is balanced by a reduction in natural emissions, and that the resultant net change is insignificant" (Armannson, 2005).
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[26] The State of California's Assembly Bill 32 (signed into law in 2006) includes a number of initiatives aimed at reducing state-wide greenhouse gas emissions. In 2008 CARB approved regulations requiring power generators to comply with monitoring and reporting guidelines regarding GHG emissions generated by their facilities. As a result, geothermal power plant operators have been forthcoming with current and accurate emissions data.
[27] California Energy Commission. Annual Generation. Retrieved April 17, 2012 from http://www.energyalmanac.ca.gov/electricity/web_qfer/Annual_Generation.php?goSort=SumOfnetMWh&year=2010.
[28] Beginning January 2012, the threshold has been raised to 10,000 MTCO2e for both CO2 and CH4, and CARB expects that the list of reporting geothermal facilities may change as a result.
[29] Communications with John Pritchett, SAIC, Sept. 26, 2010.
[30] Emissions data reported to CARB are presented in a "2010 Emissions Summary" file in metric tons of carbon dioxide equivalent (CO_2e) on per-facility basis. For geothermal facilities, the CO_2e figure is comprised almost exclusively of CO_2, with

small amounts of methane (CH_4), nitrous oxide (N_2O), and sulfur hexafluoride (SF6) reported at some facilities. CH_4, N_2O and SF6 figures were converted to their carbon dioxide equivalent by multiplying each figure by its global warming potential (GWP). CARB used the following GWP values for the GHGs mentioned: CH_4 (GWP=21), N_2O (GWP=310), SF6 (GWP=23,900). Non-carbon dioxide emissions from geothermal facilities did not have a significant impact on the weighted average lbCO_2e/MWh total, adding less than one lbCO_2e/MWh to the overall statewide geothermal GHG emissions rate.

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