PROCEEDINGS, 42nd Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, February 13-15, 2017
SGP-TR-212

Greenhouse Gas Emissions from Geothermal Power Production

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Keywords: Geothermal greenhouse gas emissions, GHG, natural processes affecting GHG emissions, effects of production on GHG emission, knowledge gaps, *ex ante* estimation guidelines

ABSTRACT

Geothermal power production may result in significant greenhouse gas (GHG) emissions. GHG emissions from geothermal power production, mostly in the form of CO_2, are generally low in comparison to traditional base load thermal energy power generation. However, as the geothermal sector has expanded, a wider range of geothermal resources have been brought into exploitation, including geothermal systems with relatively high GHG concentrations in the reservoir fluid. Recent data from Italy (Mt. Amiata) and a number of sites in Turkey show that GHG emissions from geothermal power plants can be higher than 500 g/kWh and in some cases higher than 1000 g/kWh or on par with or higher than emissions from coal fired power plants.

The best estimate for a global average CO_2 emission factor from geothermal plants is 122 g/kWh from Bertani and Thain (2002). Recent CO_2 emission factors for Iceland (2012), California (2014), New Zealand (2012), and Italy (2013) were 34, 107, 104 and 330 gCO_2/kWh, respectively. Data to calculate the contribution of CH_4 to geothermal GHG emissions are only available for New Zealand, where this amounts to 18.3 gCO_2e/kWh. These national (and state-wide) average emission factors are all lower than typical emission factors for natural gas power plants (around 450 g/kWh) illustrating that, on average, geothermal plants emit significantly less GHG compared to fossil fuel fired thermal plants.

A number of processes can affect the amount of GHGs released from geothermal power plants over time. These can be natural processes, such as when magmatic events cause temporary influx of CO_2 into a geothermal reservoir resulting in increased GHG emission factors. In other cases, production from the reservoirs may result in changes in GHG emission factors from geothermal power plants. This can result in decreased emissions with time, such as when return of gas-free reinjection fluid dilutes the pristine geothermal fluid or when progressive boiling of the same fluid results in gradual degassing. On the other hand, formation of a steam cap at shallow levels in geothermal reservoirs may result in temporary increase in gas content of steam produced from shallow levels and causing an increase in GHG emission factors for the power plant. More project data are needed to allow better understanding of how GHG emissions from geothermal power plants evolve with time.

The effects of geothermal power production on diffuse CO_2 emissions through soil are still not fully understood and may vary drastically in different types of geothermal systems. In Reykjanes, Iceland, diffuse CO_2 emissions have increased fourfold from the commissioning of a 100 MW geothermal power plant in the field in 2006. Historical heat flow measurements from Wairakei, New Zealand, suggest that power production also resulted in increased CO_2 emission through the soil in that field. In Larderello, Italy, the opposite occurred, i.e. geothermal power production has resulted in significant reduction of surface activity and thus GHG emissions through fumaroles and soil.

It is vital for the geothermal sector to have as complete understanding of the environmental impacts of geothermal power production as possible. This includes not only measuring GHG emission factors at the commissioning of power plants, but also understanding how GHG emission factors change over time and how power production affects GHG emissions through soil. The World Bank and other Multilateral Development Banks are increasingly paying attention to these issues. The World Bank has recently developed a scheme to estimate, *ex ante*, GHG emission factors from geothermal power projects financed by the institution. The World Bank is encouraging developers that benefit from World Bank financing to collect project data that will allow improved understanding of these issues. The geothermal sector, as a whole, is encouraged to collect and publish more data that will improve the collective understanding of GHG emissions from geothermal power production and the underlying processes.

1. INTRODUCTION

Geothermal is a renewable source of energy that can be used directly for heating or for power production. Geothermal utilization, particularly power production, may result in significant greenhouse gas (GHG) emissions. GHG emissions from geothermal power production is generally an order of magnitude lower than those from traditional base load thermal energy power generation facilities. This is mainly due to the fact that the large majority of installations that exist today draw their geothermal energy from geothermal reservoirs with low GHG concentrations. However, as the geothermal sector has expanded, a wider range of geothermal resources have been brought into exploitation, including geothermal systems with relatively high GHG concentrations in the reservoir fluid, resulting in significant GHG emissions from geothermal power plants.

It has become increasingly apparent in recent years that geothermal power plants can, in rare instances, release significant quantities of GHG into the atmosphere. The World Bank and some other Development Finance Institutions are committed to keep an account of

GHG emissions resulting from or avoided by their investment operations. These institutions tend to use constant average emission factors for geothermal emissions calculations, which may not be appropriate considering the wide range of emission factors observed globally. It is, thus, critically important for such institutions to establish a good understanding of the range of expected GHG emission factors from geothermal power plants and the processes that may affect these emissions over time.

This paper draws on a recent Technical Report published by the Energy Sector Management Assistance Program of the World Bank (ESMAP, 2016) that addresses GHG emissions form geothermal power projects from the perspective of the World Bank and other Development Finance Institutions. This paper we gives an overview of the best available estimates of GHG emission factors for geothermal power plants, both globally and for individual countries, and discusses the geological conditions that lead to anomalously high GHG emissions. Finally, we address two important open questions that affect how GHG emissions from a given project are estimated *ex ante* over the lifetime of the project, i.e. how GHG emission factors from geothermal power plants evolve over time and how geothermal power production may affect the emission of geothermal gas through the surface. To this end, we suggest that the geothermal community collaborates to increase the level of understanding of these issues.

2. NATURAL SOURCES AND SINKS OF CO_2 IN GEOTHERMAL SYSTEMS

Carbon dioxide and methane (CH_4) are significant GHGs that exist in geothermal fluids. While CO_2 is the most abundant, CH_4 is generally present in low concentrations as well. However, due to its relatively strong Global Warming Potential (28 times that of CO_2[1]), CH_4 may still have a significant contribution to the overall GHG emissions from geothermal power plants. Data on CH_4 emissions from geothermal power plants are available for only a few systems, for which usually there exist CO_2 emission data. As a result, it is difficult to assess the CH_4 contribution to GHG emissions from geothermal power production accurately. Available data suggest that CH_4 emissions from geothermal power plants range from a few percent to more than a quarter of the total emissions in a few extreme cases in terms of CO_2 equivalents (see examples of Iceland and New Zealand in Section 3.2 below). Here it is assumed that the magnitude of the global warming potential of CH_4 emissions from geothermal power plants is significant but generally smaller than that of CO_2. Thus, as data on CH_4 emissions from geothermal power plants is limited, the discussion below will focus on CO_2.

The sources and sinks of CO_2 in geothermal fluids are illustrated schematically on Figure 1. There are three main sources of CO_2 in geothermal fluids. A small fraction of the CO_2 in a geothermal reservoir may have the same origin as the geothermal fluid itself, fluid being dissolved in the recharging fluid, sea water or meteoric water, when entering the system. This is generally an insignificant fraction of the total CO_2 dissolved in geothermal fluids.

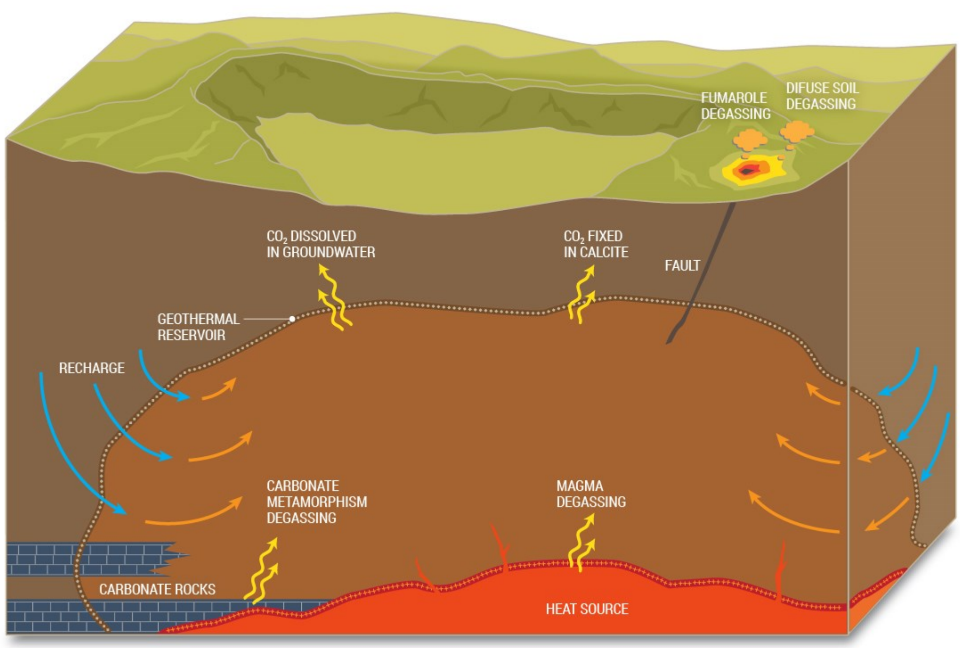

Figure 1: Schematic diagram of a volcanic geothermal system showing the natural sources (recharge, rock dissolution, decarbonization or carbonate rocks or magma degassing) and sinks (dissolution in groundwater, precipitation in calcite, and emission through fumaroles or through soil) of CO_2.

Secondly, a significant fraction of the CO_2 in geothermal fluids may be derived from the host rock of the geothermal system. Igneous rocks, which are the dominant rock type in volcanic geothermal systems, contain a small amount of carbonate that is released to the geothermal fluids due to chemical interactions between the rocks and the fluids. The concentrations of CO_2 in volcanic geothermal systems can therefore be expected to be moderate if rock dissolution is the major source of CO_2 in the fluid. Other rock types may

[1] Assuming 100 year time horizon (IPCC, 2014)

release larger quantities of CO_2 into the geothermal fluids. This is most pronounced for carbonate rocks. Such rocks may release large amounts of CO_2 to the geothermal fluids upon dissolution or through metamorphic processes at high temperatures. Carbonate hosted high temperature geothermal systems are not common, but they do occur (notably in the Tuscany region of Italy and western Turkey) and they are characterized by significantly higher CO_2 fluid concentrations than other geothermal reservoirs. Other types of sedimentary rocks contain variable amounts of carbonates, resulting in a range of CO_2 concentrations in the geothermal fluids.

Finally, CO_2 may enter the geothermal reservoir from below, either from deep crustal or mantle sources or from magma bodies, which are the heat sources of many volcanic geothermal systems. Magmatic CO_2 can enter geothermal reservoirs continuously, such as in Mt. Amiata, Italy or Ohaaki, New Zealand (Haizlip et al., 2013) or in pulses related to magmatic intrusions, such as in Krafla, Iceland. Figure 2 shows the CO_2 emission factors for the Krafla power plant in N-Iceland from 1979 to 2013 (based on Baldvinsson et al., 2009 and data from Landsvirkjun's annual reports). The CO_2 content of the Krafla geothermal fluid increased drastically as a result of volcano-tectonic events between 1975 and 1984, commonly referred to as the Krafla Fires. During these events basaltic magma was released from the magma chamber 21 times and 9 eruptions occurred. One consequence of the magma movements was injection of large amounts of CO_2 to the geothermal reservoir, particularly to the western part. This resulted in high emission factors from the Krafla Power Plant during the Krafla fires. The gas content of the reservoir fluid gradually decreased after the cessation of the Krafla Fires in 1984. Emission factors spiked again temporarily in 1999 when a second 30 MW unit was added and new production wells taken into production. Since 2005 the Krafla CO_2 emission factors have been in a declining trend.

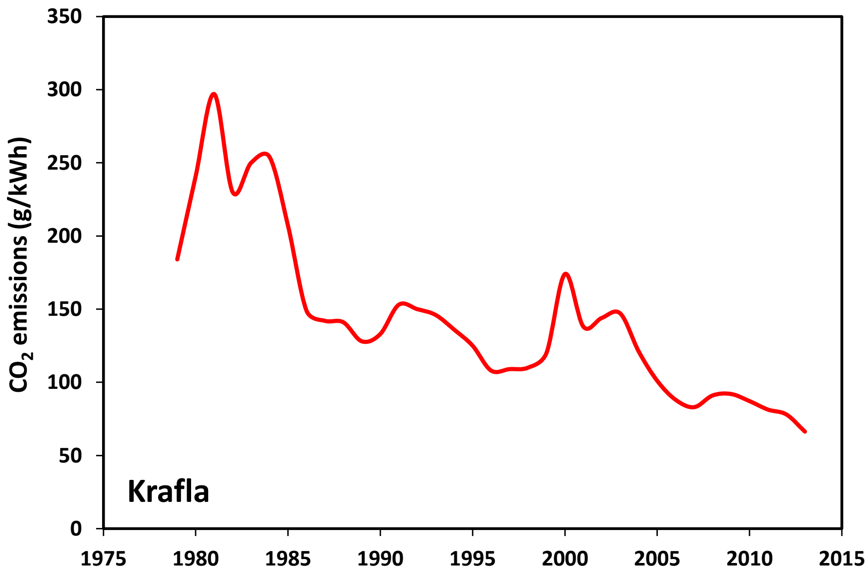

Figure 2: Emission factors from the Krafla geothermal power plant.

The sinks of geothermal CO_2 include precipitation of carbonate minerals in, or above the geothermal reservoir, emission to the atmosphere through steam vents or diffusely through the soil, and dissolution in ground waters after ascent from the geothermal reservoir. Geothermal steam emitted from steam vents may, in some cases, be a good indicator of the composition of the gas in the reservoir. However, secondary processes, such as steam condensation, boiling of shallow ground waters, and chemical reactions between gases in the steam and the bed rock and soil may significantly alter the steam composition (Arnórsson et al., 2007). Chemical reactions between CO_2 in the geothermal fluids and silicate and carbonate minerals may control the concentration of dissolved CO_2 in the fluid, essentially buffering the CO_2 concentration in the reservoir fluid to a certain level at a given temperature. These reactions are relatively slow to equilibrate and as a result the mineralogical control over the concentration of dissolved CO_2 in geothermal fluids does not always apply, i.e. the CO_2 concentration in the reservoir fluid can in some cases be either higher or lower than dictated by the mineralogical equilibria.

3. GHG EMISSIONS FROM GEOTHERMAL POWER PLANTS

Life Cycle Analyses (LCA) are increasingly used to assess emissions from power projects (among many other infrastructure projects). According to the LCA approach, emissions are assessed for the *Plant Cycle* and *Fuel Cycle* separately. In the context of geothermal projects, the Plant Cycle GHG emissions include emissions related to the construction of the power plant and surface installations, drilling and completion of wells, the production of the materials needed for these installations, and the eventual decommissioning of the facilities, normalized over the lifetime of the project. The Fuel Cycle emissions refer to the release of geothermal GHG during the energy conversion process. The Fuel Cycle emissions are sometimes referred to as *operational emissions* or *fugitive emissions*. Most of the available literature on GHG emissions from geothermal projects refers to the Fuel Cycle emissions only and only a handful of relatively recent publications have addressed the Plant Cycle emissions from geothermal power production. The sections below present an overview of the available information on Plant Cycle and Fuel Cycle emissions from geothermal power plants.

3.1 Plant Cycle GHG Emissions from Geothermal Power Plants

The available information on Plant Cycle emissions indicate that these emissions are in the range of 2 to almost 20 gCO_2e/kWh assuming a project lifetime of 30 years. Sullivan et al. (2013) estimate that the Plant Cycle emissions for a hypothetical 50 MW flash plant in southwest United States would be in the range of 2 to 5 gCO_2e/kWh and their estimate for a 10 MW binary plant in the same location was 5 to 6 gCO_2e/kWh. The numbers are in good agreement with the results of Marchand et al. (2015) who estimated Plant Cycle emissions for three expansion scenarios for the Bouillante geothermal field in Guadeloupe to be in the range from 3.8 to 5.2 gCO_2e/kWh. Karlsdóttir et al. (2015) estimated that Plant Cycle emissions from the Hellisheidi plant in Iceland would be of the order of 8.4 to 10.8 gCO_2e/kWh. The highest value reported for Plant Cycle emissions is from Hondo (2005); 15 gCO_2e/kWh. However, Hondo (2005) assumed a capacity factor of only 0.6 for his hypothetical plant. If a value of 0.9 is used for the capacity factor, a value more commonly cited for geothermal power plants, the resulting Life Cycle emission is 10 gCO_2e/kWh. Finally, Rule et al. (2009) reported a Plant Cycle emission value of 5.6 gCO_2e/kWh for the Wairakei geothermal power plant in New Zealand. However, this value corresponds to a project life time of 100 years. When Rule et al.'s (2009) value is converted to a basis of a 30 year lifetime the resulting Plant Cycle emission value could be as high as 18.6 gCO_2e/kWh.

Although the above data are too scarce to derive a statistically significant average value for Plant Cycle GHG emissions from geothermal power projects, the variation among different studies is relatively small. Considering the range and the magnitude of operational GHG emissions from geothermal projects (see below) it is acceptable to assume that Plant Cycle GHG emissions of geothermal power projects equal to 10 gCO_2e/kWh for a standard project life time of 30 years. While the data presented by Sullivan et al. (2013) and Marchand et al. (2015) are significantly lower than 10 gCO_2e/kWh, the difference, amounting to some 5 gCO_2e/kWh, is insignificant in the context of the overall GHG emissions from geothermal power projects.

3.2 Fuel Cycle GHG Emissions from Geothermal Power Plants

The most complete global survey on CO_2 emissions to date was presented by Bertani and Thain (2002). Their study was based on emissions and power production information from 85 geothermal power plants in 11 countries, with a combined installed capacity of 6,648 MW, which amounted to 85% of the global geothermal power capacity in operation in the year 2001. The power plants included in the 2001 global study still amount to more than 50% of the total installed capacity today and can thus be considered a fairly reliable indicator of the range and global average of CO_2 emissions from geothermal power plants. The study found that the range of CO_2 emissions from geothermal power generation was from 4 to 740 g/kWh, and the weighted average was found to be 122 g/kWh. Emissions from binary plants were not included in these numbers (Bertani, personal communication 2014). It should also be noted that the survey focused exclusively on CO_2 emissions, i.e. CH_4 emissions were not considered. The results of this global survey were presented in a short article in IGA News and as a result limited details are available. However, these results are supported by CO_2 emission data available from different countries. Figure 3 shows the weighted average and range of geothermal emission factors reported by Bertani and Thain (2002) and the results of other regional surveys discussed below.

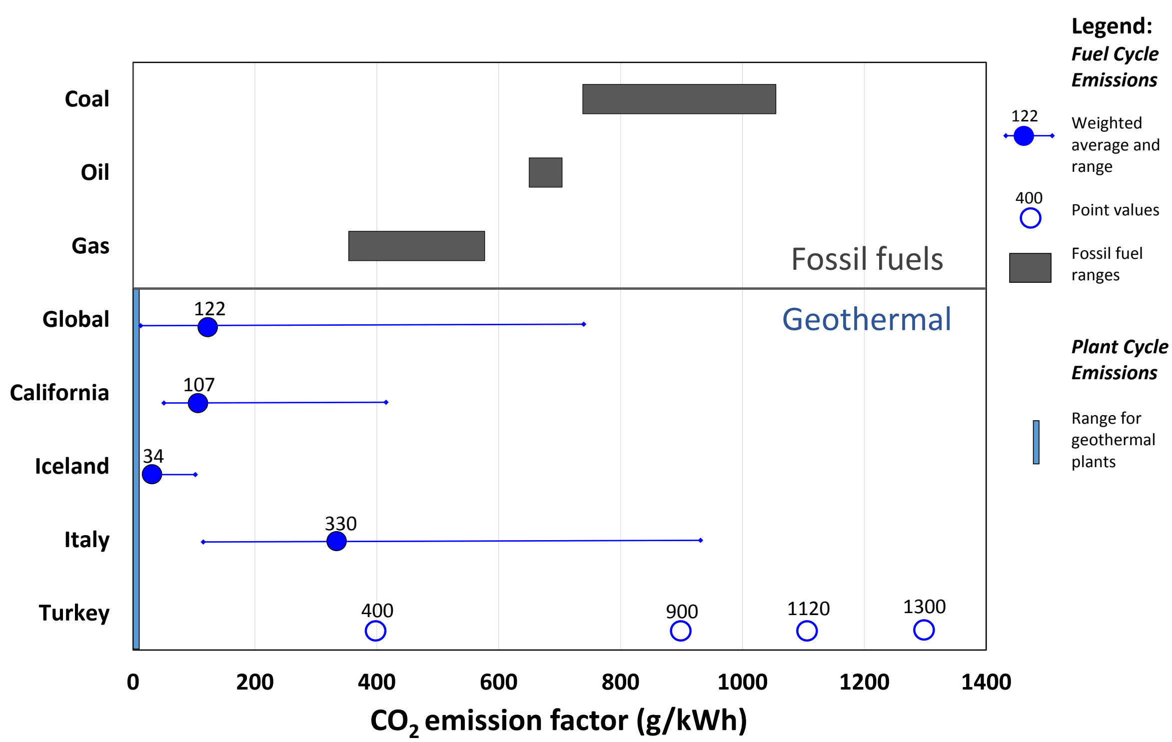

Figure 3: Weighted average and range of emission factors from geothermal power plants. The range of Plant Cycle emissions is shown with a light blue box. Emission ranges for power plants using fossil fuels are shown with gray bars.

Bloomfield et al. (2003) reported an estimated average CO_2 emission factor of 91 g/kWh from power plants in the US. They state that non-emitting binary plants amounted to 14% of the total capacity of the plants included in their study. The CO_2 emissions from the remaining 86% of the plants, i.e. the flashing steam and dry steam plants, can then be computed to be 106 g/kWh. Bloomfield et al. (2003) do not report details on the range of emissions from the US plants included in the study, nor the total number of plants and their capacity, but it is implied that all geothermal power plants in the US are included. The total installed capacity in the US at the time was about 2,500 MW (Lund et al., 2005). Recent data on CO_2 emissions and power generation of geothermal power plants in California (California Air Resources Board, 2014; US DOE, 2014) allow calculation of CO_2 emission factors for some these plants in the period 2011 to 2013. The results show a fairly wide range of emission factors. In 2013 the highest CO_2 emission factors were at the three power plants at Coso, ranging from 150 to 300 g/kWh with a weighted average of 245 g/kWh. CO_2 emissions from the Geysers power plants in 2013 were more moderate, ranging from 41 to 76 g/kWh with a weighted average of 45 g/kWh.

Data presented in New Zealand's Sixth Communication to the United Nations Framework Convention on Climate Change and the Kyoto Protocol (2013) allow calculation of CO_2 equivalent emissions from the country's geothermal power plants in 2012: 122.7 gCO_2e/kWh. Of these emissions, some 104.4 g/kWh are CO_2 and the remaining 18.3 gCO_2e/kWh correspond to CH_4 emissions.

Baldvinsson et al. (2011) presented data for CO_2 emissions from all the Icelandic geothermal power plants in the period from 1970 to 2009 and ESMAP (2016) added emission factors for 2010 to 2013. The weighted average CO_2 emission from the six power plants in 2009 was 50 g/kWh, with a range of 21 to 92 g/kWh. Emission factors have decreased slightly in recent years according to emission data provided by Icelandic geothermal power producers. In 2013 CO_2 emission factors ranged from 18 to 78 g/kWh and the weighted average was 34 g/kWh. Note that these numbers represent CO_2 emissions only, i.e. CH_4 emissions are not taken into account. Available CH_4 emission data from four out of six geothermal power plants in Iceland suggest that CH_4 emissions could amount to some 5% of GHG emissions from Icelandic geothermal power plants.

CO_2 emissions from Italian geothermal plants are generally rather high. Emission factors for power plants in Larderello, Mount Amiata, Val di Cornia and Travale-Chiusino were computed from data from ARPAT (2012, 2013; Regional Environmental Protection Agency for Tuscany). Data were available for five years in the period 2002 to 2013. In this period, the weighted average CO_2 emission factors decreased gradually from 422 to 330 g/kWh. In 2013, CO_2 emission factors ranged from 114 to 827 g/kWh and the weighted average was 330 g/kWh.

3.3 High emission outliers

The highest value for geothermal CO_2 emissions reported by Bertani and Thain (2002) was 740 g/kWh. Bertani and Thain (2002) did not report standard deviation of emission factors for the plants included in their global survey. However, according to Bertani (personal communication, 2016) the standard deviation of the emission factors was substantial, 163 g/kWh, suggesting that already at that time there were several geothermal power plants with significant GHG emissions. Since 2002, new emissions data from several high emission geothermal power plants have become available. Below, two well reported examples of high emission geothermal power plants are described, i.e. the power plants in West Turkey and in Mount Amiata, Italy. What the high CO_2 systems in Turkey and Italy systems seem to have in common is that they are hosted in carbonate bearing rocks, although anomalous deep mantle CO_2 may also contribute to the high values in Mount Amiata.

3.3.1 Buyuk Menderes Graben and Gediz Graben, Western Turkey

The range of emissions from geothermal power plants in the Buyuk Menderes graben is reported to range from 900 to 1,300 g/kWh (Wallace et al, 2009; Haizlip et al., 2013; Aksoy, 2014). Aksoy (2014) published CO_2 emission factors for nine power plants in seven geothermal fields in Turkey. The emission factors range from 400 to 1,300 g/kWh and the weighted average (based on installed capacity) is 1,050 g/kWh. Eight of the nine power plants considered by Aksoy (2014) are located in the Buyuk Menderes graben, where most of the feasible geothermal resources for power production in Turkey have been identified (Basel et al., 2010). The second most developed region for geothermal power production in Turkey is Gediz Graben, located north of the Buyuk Menderes graben. The preliminary information from this area indicates that CO_2 emission factors are similar to those of the plants in the Buyuk Menderes graben. It should be noted that not all the CO_2 brought to surface by geothermal production in Turkey is released directly to the atmosphere. Some of the CO_2 from the geothermal fluid is captured and sold off as dry ice and liquid CO_2 at four of the geothermal power plants in Turkey (EBRD, 2016).

The high CO_2 emissions from geothermal power plants in Buyuk Menderes and Gediz grabens are a result of an unusual geological setting. This area, in western Anatolia, is characterized by extensional tectonics, resulting in graben formations and crustal thinning (Haizlip et al., 2013). High regional heat flow, resulting from crustal thinning appears to be the main source of heat for these geothermal systems (Haizlip et al., 2013; Aksoy et al., 2015). This region is also characterized by an abundance of carbonate sedimentary and metamorphic rocks, such as limestone and marble. The high concentrations of CO_2 in the geothermal fluids in the region seem to result from thermal breakdown of carbonate minerals in the reservoir rocks (Haizlip et al., 2013; Aksoy et al., 2015).

3.3.2 Mount Amiata, Italy

The geothermal power plants at Mount Amiata, Italy, provide another example of high GHG emissions. Bravi and Basosi (2014) report emissions from the Bagnore and Piancastagnaio power plants in the period from 2002 to 2009 in terms of CO_2 and CO_2 equivalents. The range of CO_2 emissions from the two areas in this period was from 245 to 779 g/kWh and the weighted average was 497 g/kWh. The average value for CO_2 equivalent emissions was 693 g/kWh and the range was 380 to 1045 g/kWh.

Mount Amiata is a Quaternary volcano in southern Tuscany. It is thought that a granitic intrusion related to the volcano is the heat source for the two geothermal fields that occur on the South West and South East flanks of the volcano (Haizlip et al., 2013). Both systems consist of a shallow reservoir with a very gas rich steam cap and hot (>300°C) deep reservoir. Carbonate rocks are common in the shallow reservoir and exist to some extent in the deep the reservoirs of both systems and likely contribute to the high gas concentration in the geothermal fluids (Frondini et al., 2009; Haizlip et al., 2013). However, $\delta^{13}C$ isotope data suggest that a significant fraction of the CO_2 in the geothermal reservoirs originates in the mantle (Frondini et al., 2009). Deep mantle degassing occurs on a regional scale under large parts of Italy (Gambardella et al., 2004).

4. EFFECTS OF POWER PRODUCTION ON THE CO_2 BUDGET OF GEOTHERMAL SYSTEMS

Extraction of fluid from high temperature geothermal reservoirs affects the balance between sources and sinks of CO_2 in a complex way that can evolve over time and space and affect the emission factors. The most important processes are progressive boiling of the reservoir fluid, return of gas depleted reinjection brine, steam cap formation, and the effects on surface activity (e.g. fumaroles and steaming grounds, etc.). These processes are illustrated on Figure 4 and discussed in the following sections.

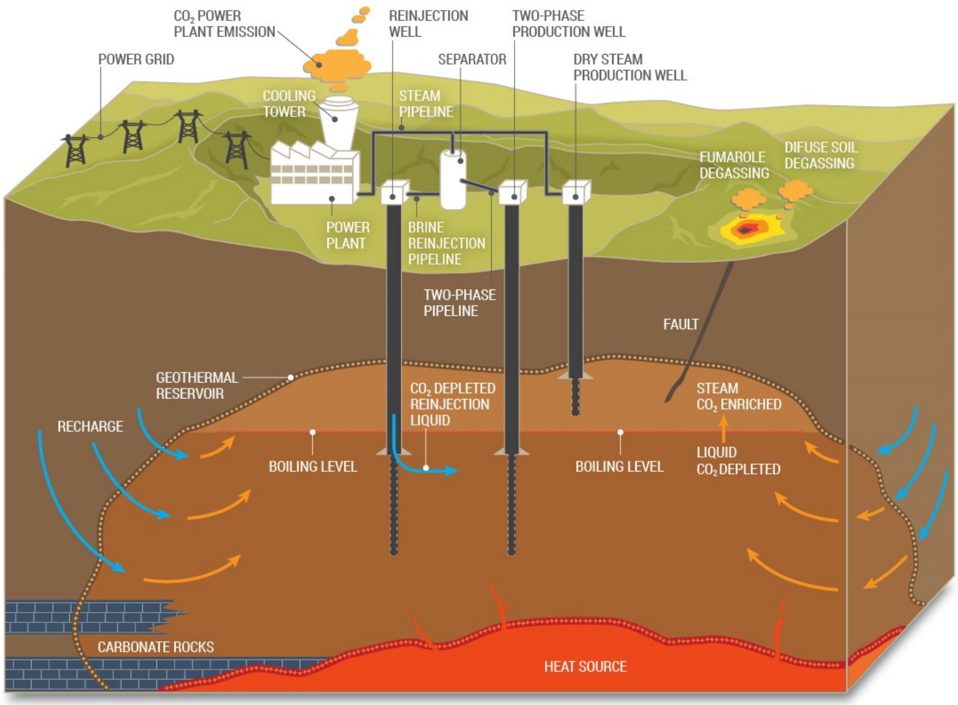

Figure 4: Schematic diagram of a volcanic geothermal system highlighting processes affecting CO_2 emissions as a result of large scale removal of fluid (mass production) from the system.

4.1 Gradual decline in gas emission due to progressive boiling and reinjection

Gradual decline in gas emissions from geothermal power plants has been observed in a number of cases. Although this is generally associated with return of gas depleted reinjection fluid, this trend has also been observed, to a lesser degree, in systems where reinjection is not practiced. The reinjected fluids, i.e. the brine and sometimes the condensate, are characterized by very low gas concentrations and will tend to dilute the reservoir fluid with respect to dissolved gases. Return of reinjected fluid may thus have a positive effect on the gas concentration in the produced steam, i.e. resulting in gradual decrease of gas concentrations in the geothermal reservoir fluid and thus lowering emission factors with time. Benoit and Hirtz (1994) reported that gas emissions from the Dixie Valley power plant in Nevada, USA, decreased from 69 g/kWh in 1988 to 42 g/kWh in 1992 as a result of returning reinjection water to the production wells. The same has occurred in Kizildere, Turkey, where the CO_2 concentration in the reservoir fluid decreased by 15% from 1984 to 2000 (Haizlip et al., 2013). Similarly, Glover and Scott (2005) report 16 to 30% decrease in CO_2 content of the reservoir fluid in Ngawha, New Zealand, due to reinjection after only 6 years of production.

The relationship between reinjection and gas concentrations may be more complex in steam dominated reservoirs even if the reinjected water is gas depleted. Reports from the Geysers field in California indicate that gas concentrations in steam produced from different parts of the reservoir may either increase, decrease or remain constant in response to injection of surface waters into the reservoir (Klein et al., 2009; Beall et al., 2007).

As the available information on the nature of gradual decline in gas concentrations of geothermal reservoir fluids is limited and equivocal, it is not recommended to assume that gas concentrations in geothermal reservoir fluids will decrease with time when future emissions from geothermal projects are assessed. However, if more project data become available it might be possible to make a rough estimate of how the gas concentrations in geothermal fluids would evolve with time, particularly for projects using reservoirs that are already in production.

4.2 Steam cap formation

Large scale removal of fluids as a result of geothermal power production may lead to reduced pressure in the reservoir. For systems that are close to boiling such pressure drop will result in increased boiling in the reservoir. When this happens, the part of the reservoir above the boiling level becomes vapor dominated. Because dissolved gases partition preferentially to the vapor phase, this process leads to the formation of steam with relatively high gas concentration while the reservoir liquid affected by this boiling is left depleted of geothermal gas, including CO_2, to some degree. This process, sometimes referred to as a steam cap or steam zone formation, may result in increased gas concentrations in steam from the steam cap, but decreased gas concentrations in steam produced from the deeper, liquid dominated part of the reservoir (c.f. Ármannsson et al., 2005; Glover and Mroczek, 2009). Steam caps do not form in all geothermal systems and even when they do form, they may not have very high gas concentrations.

Steam cap formation may have different effects on the gas concentration in the steam produced from the reservoir depending on the production strategy. The net effect of a steam cap formation on the CO_2 emissions from a given field will depend, to some degree, on the ratio of production from deeper and shallower levels.

The gas concentration in steam caps may decrease with time. This has been observed in several places such as at Mount Amiata, Italy (Barelli et al., 2010) and Svartsengi, Iceland. In Svartsengi CO_2 emissions increased from 100 to 160 g/kWh in the late 1980s to 300 to 470 g/kWh in the mid-1990s. Since 2000 the emissions from Svartsengi have gradually decreased and have now levelled off at around 100 g/kWh. The reason for the peak in CO_2 emissions in Svartsengi in the 1990s was the increased production from a steam cap that formed at shallow levels in the North East part of the field in the mid-1980s. The gas concentration in the steam that formed in the steam cap was about an order of magnitude higher than in steam formed by flashing geothermal brine in other parts of the field (5 wt% compared to 0.5 wt%; Bjarnason, 1996). Decreasing emissions from Svartsengi in the last 15 years is a result of gradual decrease in CO_2 concentration in the steam cap to less than 2 wt% in recent years (Óskarsson, 2014) and of increased production from other parts of the reservoir relative to the steam cap.

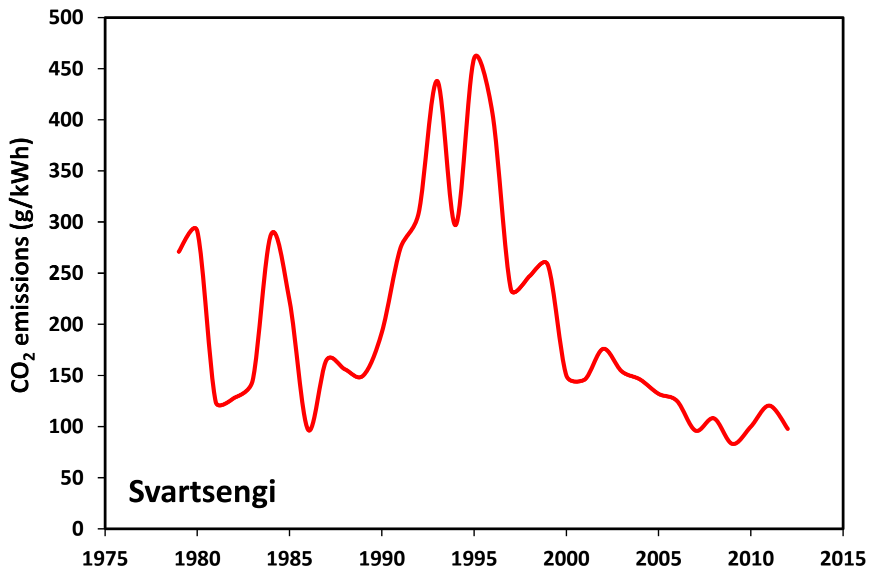

Figure 5: CO_2 emission factors for the Svartsengi geothermal power plant.

4.3 Changes in surface activity

Pressure reduction in high temperature reservoirs due to production can, as mentioned above, lead to increased boiling in the reservoir. The increased boiling can in turn lead to increased surface activity. Examples of this are increased steam flow through fumaroles and increase of soil temperature and the areal extent of hot ground. This may be a common phenomenon, but it has been not been widely documented. To the authors' knowledge, these effects have been quantitatively documented in only three geothermal fields, i.e. Wairakei and Ohaki, New Zealand (Allis, 1981; Rissman et al., 2012) and Reykjanes, Iceland (Fridriksson et al., 2006, 2010; Óladóttir and Fridriksson, 2015). In the Karapiti area in Wairakei the surface heat flow (i.e. loss of heat through the ground-air interface; heat loss can be used as a proxy for CO_2 flow through the surface assuming convective heat transfer and constant CO_2 concentration in the steam) increased by an order of magnitude, from 40 MW_t to 420 MW_t, between 1958, when the first unit was commissioned, and 1964 (Allis, 1981). By 1978, the surface heat flow had declined to about 220 MW_t and has not changed significantly since then (Glover et al., 2001; Glover and Mroczek, 2009).

At Reykjanes, South West Iceland, a 100 MW_e power plant was commissioned in 2006. Figure 6 shows the evolution of the CO_2 emissions from the Reykjanes system from 2004 through 2014. The CO_2 diffuse emissions through the soil were about 13 t/day in 2004 and 2005 but increased after the commissioning of the power plant to 18.5 t/day in 2007 (Fridriksson et al., 2010, 2015). Since then, the CO_2 emissions through the soil have gradually increased to 51 t/day in 2013 (Óladóttir and Fridriksson, 2015). The CO_2 emissions from the power plant have decreased by almost 25% from 2007 to 2014, but the total emissions from the system continue to increase because of the continuous increase in diffuse degassing emissions.

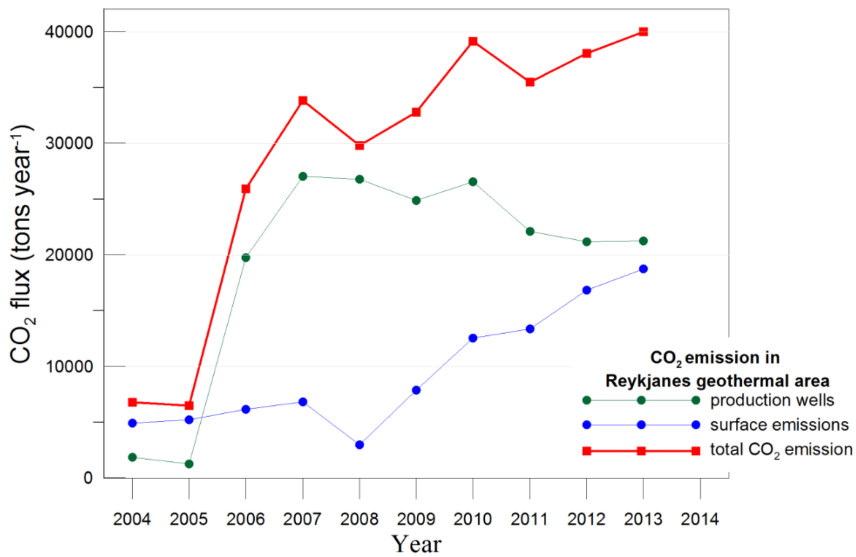

Figure 6: CO_2 emissions from the Reykjanes Geothermal system, Iceland. Red curve show the combined emissions from power production (green) and diffuse CO_2 degassing through surface (modified from Óladóttir and Fridriksson, 2015).

Rissmann et al. (2012) reported a 70% increase in heat flow in the Western part of the Ohaaki geothermal field in New Zealand after 20 years of production. No change in heat flow was noticed in the Eastern part of the field. It can thus be concluded that the total increase in heat flow through soil, and by proxy CO_2 emission through soil from the system as a whole, was of the order of 35% over a period of 20 years. Increase in heat flow and CO_2 emissions from the surface is likely to be particularly pronounced in systems where the pressure drop is abrupt in response to production and where the geothermal reservoir is connected to the surface, i.e. where geothermal manifestations are abundant. Unfortunately, very few studies have allowed quantification of this effect.

In contrast to the above observations from Wairakei and Reykjanes, Bertani and Thain (2002) argue that geothermal power production may cause a decrease in gas emissions through natural pathways from geothermal reservoirs. Consequently, they argue that "a very strong case can be made for subtracting the pre-development natural emission rate from the rate being released by the operation of the geothermal development". In support of this, they state that CO_2 emissions through natural pathways, i.e. soil and fumaroles, has noticeably and measurably decreased in Larderello as a result of geothermal power production from that field. These observations of decreased surface activity at Larderello are supported by pictures and descriptions from travelers that visited these areas prior to exploitation (see Figure 7). According to these accounts, the entire Larderello area was covered by active surface manifestations such as fumaroles, boiling pools, and steaming grounds, earning it the name Devil's Valley. Over the last several decades, power production from the Larderello system has brought about pressure decrease in the reservoir and, as a result, the natural degassing from the system has almost completely ceased (R. Bertani, personal communication). Similarly, Frondini et al. (2009), citing Sammarco and Sammarco (2002), suggest that geothermal power production at Mount Amiata, Italy, may have resulted in decreased natural gas emissions at that site.

Figure 7: Surface activity in Larderello in the 1800s (left; Jervis, 1868) and in the 2000s (right; ENEL Green Power). Geothermal surface activity, and by proxy GHG emissions through soil, have largely disappeared in response to power production in an area previously characterized by vigorous steam vent activity.

Due to the limited number of studies that have directly measured the effect of geothermal power production on CO_2 emissions through natural pathways, it is not possible to make general statements about the magnitude of this effect, which is likely to vary greatly from one site to another. It is also possible that steam dominated reservoirs respond differently to power production as compared to liquid dominated reservoirs as suggested for Larderello by Bertani and Thain (2002). The relationship between emissions through soil and fumaroles and geothermal power production needs to be studied in more locations in order to better understand the underlying processes.

5. EX ANTE ESTIMATION OF EMISSION FACTORS FOR GEOTHERMAL PLANTS

The World Bank and other Development Finance Institutions apply carbon accounting to their projects. This involves estimating future GHG emissions caused or offset as a result of their activities. The discussion above clearly illustrates that this is not a trivial task for geothermal projects; the range of emission factors for geothermal plants is large, emission factors can change with time, both in response to production and also due to natural processes, and finally CO_2 emissions through soil may increase or decrease in response to production. ESMAP (2016), nevertheless, developed guidelines for assessing future emissions for geothermal projects outlined in Figure 8.

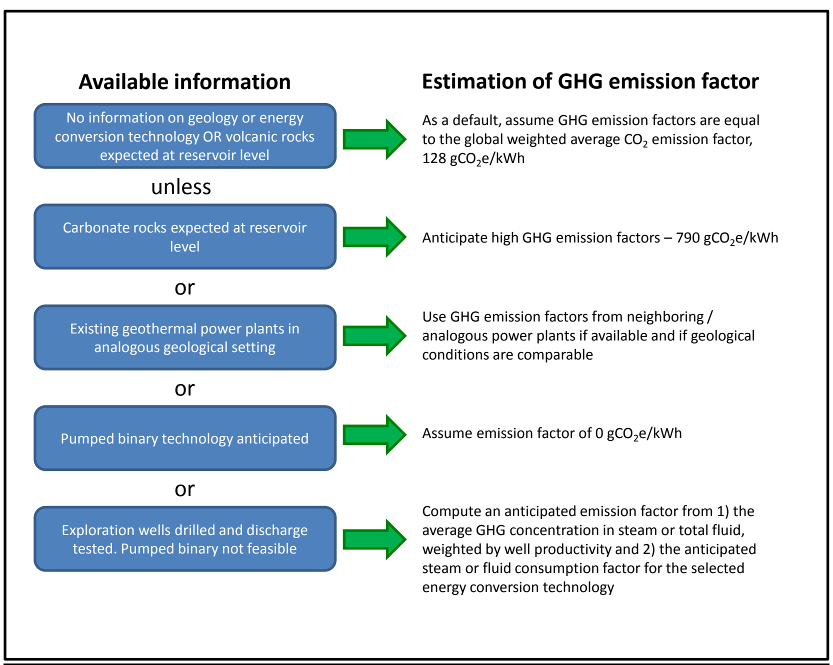

Figure 8: Decision tree for estimating GHG emission factors *ex ante* for geothermal projects depending on the amount of available information.

As can be seen from Figure 8 the ESMAP (2016) approach for estimating *ex ante* emissions from geothermal power plants applies to geothermal projects in different stages of development. For greenfield projects in unknown geological conditions, it is recommended that the emission factor is assumed to be equal to the global average determined by Bertani and Thain (2002) plus 5% to account for contribution of CH_4. For power projects in carbonate bedrock an emission factor of 790 gCO_2e/kWh should be assumed. This value is selected by assuming a CO_2 emission factor of 750 g/kWh as the median of the range that emission from carbonate systems commonly fall within (500 to 1000 g/kWh) and adding 5% to account for CH_4. If emission data from near-by power plants in analogous geological conditions are available these data may be used to constrain the emission factors for the new plant. Zero GHG emission is to be assumed for projects where pumped, closed cycle, binary technology is to be used (note that most binary plants in high temperature systems do not fall into this category). Finally, a methodology is presented to compute emission factors for power plants where wells have been drilled and discharge tested. The scheme assumes constant emissions throughout the lifetime of the project and that the power production does not affect diffuse gas emissions through soil.

While this approach is significantly more accurate than the previous practice of applying a single generic emission factor for all geothermal projects it provides, at best, a very rough estimation of future GHG emissions. As discussed above there are a number of processes that may significantly affect the evolution of emission factors of geothermal power plants over time and these are not addressed in the scheme outlined in Figure 8. Some, such as the effects of steam cap formation and magmatic gas influx, are too erratic and rare to predict and incorporate into an *ex ante* emission estimation. For other processes, such gradual changes (decline) of emission factors and decrease/increase in diffuse CO_2 emissions through soil, the available data are too limited to justify general predictions of their impact in future geothermal projects.

In an effort to collect the necessary data to refine the scheme presented in Figure 8, the World Bank in encouraging geothermal developers benefitting from World Bank financing to collect and share project data that may eventually help close these knowledge gaps. On one hand, beneficiaries of geothermal investment projects are requested to collect emission data and over the lifetime of their projects and make these data available for evaluation of gradual changes in GHG emission factors. With sufficient volume of project data it may be possible to develop a universally applicable GHG emission factor decline rate that can be used in estimating future emissions. The data to do this already exist within data bases of individual developers and a concerted analytical effort by the geothermal sector interest groups, such as the IGA (International Geothermal Association) or GEA (Geothermal Energy Association), could quickly provide the data needed to assess the average GHG emission factor decline rate for geothermal plants and, as importantly, the range of the observed decline rates.

Much less is known about the effects of power production on diffuse CO_2 emissions through soil. In order to properly determine the effect of geothermal power production on diffuse CO_2 emissions in a given site it is necessary to carry out a measurement campaign(s) before power production commences to collect baseline diffuse emission data. Subsequently, follow-up campaigns are needed after power production has started to quantify the change in diffuse emission. Such data sets are, as noted above, very rare. The World Bank, together with European Bank of Reconstruction and Development (EBRD), has initiated a study that will collect baseline diffuse degassing data from 6 sites in Turkey were geothermal plants will be developed in the near future. Follow-up surveys will be carried out once power production has started. While the data collected in these studies will significantly increase the volume of data on the effect of geothermal power production on diffuse degassing, they will not provide a comprehensive understanding of this effect on a global scale. To achieve that, a collective effort by the geothermal community is needed.

CONCLUSIONS

There is a growing realization both within and outside of the geothermal industry that geothermal power plants may in some cases emit significant amounts of GHGs. The literature review conducted as part of this study by the World Bank shows that high GHG emissions are strongly related to the geological settings of the geothermal reservoirs. Furthermore, this study shows that despite several recent reports of high GHG emitting power plants the best estimates from global average GHG emission factor for geothermal power plants are only about a quarter of typical emission factors for gas fired power plants and just over ten percent of emission factors for coal fired power plants.

Predictions of future emissions from geothermal power plants are complicated by a host of processes that can interact in complex ways to cause significant changes in GHG emissions from geothermal power plants over time, such as steam pillow formation, injection of magmatic gases, and return of reinjection fluid. Furthermore, the limited available evidence indicates that diffuse GHG emissions through soil in geothermal fields may either increase or decrease in response to geothermal power production. More studies are needed to better understand changes of GHG emissions from geothermal power plants over time, in order to quantify the gradual decline in GHG emissions commonly observed and the changes in diffuse emissions of GHGs in response to power production.

The World Bank and other Development Finance Institutions have committed to keep accounts of GHG emissions resulting from or preferably avoided by their activities. A scheme to estimate, *ex ante*, GHG emissions of geothermal power plants has been developed by the World Bank. This scheme does not take into account any processes that may change GHG emission factors over time. In order to refine *ex ante* estimations of GHG emissions from geothermal projects, a better understanding of gradual changes in GHG emission factors is needed. It is also important to gain a better understanding of the effects of power production on diffuse emissions of GHG through soil. We call on the geothermal community to engage in a joint effort to close these knowledge gaps and thus allowing more accurate predictions of future emissions from geothermal power plants.

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