CHAPTER 8

Environmental Impacts, Attributes, and Feasibility Criteria

8.1 Scope and Approach to Geothermal Environmental Effects ____________8-3

8.2 Potential Environmental Impacts from Geothermal Development _______8-5

- 8.2.1 Gaseous emissions ____________8-5
- 8.2.2 Water pollution ____________8-6
- 8.2.3 Solids emissions ____________8-6
- 8.2.4 Noise pollution ____________8-7
- 8.2.5 Land use ____________8-7
- 8.2.6 Land subsidence ____________8-9
- 8.2.7 Induced seismicity ____________8-9
- 8.2.8 Induced landslides ____________8-10
- 8.2.9 Water use ____________8-10
- 8.2.10 Disturbance of natural hydrothermal manifestations ____________8-12
- 8.2.11 Disturbance of wildlife habitat, vegetation, and scenic vistas ____________8-12
- 8.2.12 Catastrophic events ____________8-15
- 8.2.13 Thermal pollution ____________8-15

8.3 Environmental Attributes of EGS Power Projects ____________8-16

- 8.3.1 No greenhouse gas emissions during operations ____________8-16
- 8.3.2 Modest use of land ____________8-16
- 8.3.3 Possible sequestration of carbon dioxide ____________8-16
- 8.3.4 Low overall environment impact ____________8-17

8.4 Environmental Criteria for Project Feasibility ____________8-17

8.5 Concluding Remarks ____________8-18

References ____________8-19

8.1 Scope and Approach to Geothermal Environmental Effects

In the United States, the environmental impact of any type of power project is subject to many forms of regulation. All of the following laws and regulations play a role before any geothermal development project can be brought to fruition (Kagel et al., 2005):

- Clean Air Act
- National Environmental Policy Act
- National Pollutant Discharge Elimination System Permitting Program
- Safe Drinking Water Act
- Resource Conservation and Recovery Act
- Toxic Substance Control Act
- Noise Control Act
- Endangered Species Act
- Archaeological Resources Protection Act
- Hazardous Waste and Materials Regulations
- Occupational Health and Safety Act
- Indian Religious Freedom Act.

Thus, it is highly unlikely that any geothermal power plant will be a threat to the environment anywhere in the United States, given the comprehensive spectrum of regulations that must be satisfied.

The potential environmental impacts of conventional hydrothermal power generation are widely known. Several articles and reports have documented the various potential impacts from geothermal dry-steam, flash-steam, and binary energy conversion systems. The general conclusion from all studies is that emissions and other impacts from geothermal plants are dramatically lower than other forms of electrical generation. The following references, chosen from among many possible ones, provide detailed discussions: Armstead, 1983; Armstead and Tester, 1987; Burnham et al., 1993; DiPippo, 1991a; DiPippo, 1991b; Kagel et al., 2005; Mock et al., 1997; Pasqualetti, 1980; and Tester et al., 2005.

Thus, the lessons learned from the hundreds of existing geothermal power plants can be used to ensure that future EGS systems will have similar or even lower environmental impacts.

Our focus in this report is on systems to generate electricity. Ground-source heat pumps are another means of utilizing geothermal energy on a distributed basis for space heating and cooling of buildings (see Section 7.3). The environmental impact of such systems is quite limited because they are usually installed during building construction and normally utilize a subsurface heat exchanger, buried well below the frost line. The environmental impacts of geothermal heat pumps are not addressed further, because they are beyond the scope of this study (see Mock et al., 1997.)

There are several potential environmental impacts from any geothermal power development. These include:

- Gaseous emissions
- Water pollution
- Solids emissions
- Noise pollution
- Land use
- Land subsidence
- Induced seismicity
- Induced landslides
- Water use
- Disturbance of natural hydrothermal manifestations
- Disturbance of wildlife habitat and vegetation
- Altering natural vistas
- Catastrophic events.

Despite this long list, current and near-term geothermal energy technologies generally present much lower overall environmental impact than do conventional fossil-fueled and nuclear power plants. For example, the power plant is located above the geothermal energy resource eliminating the need (a) to physically mine the energy source (the "fuel") in the conventional sense and, in the process, to disturb the Earth's surface, and (b) to process the fuel and then use additional energy to transport the fuel over great distances while incurring additional environmental impacts. Furthermore, the geothermal energy conversion equipment is relatively compact, making the overall footprint of the entire system small. With geothermal energy, there are no atmospheric discharges of nitrogen oxides or particulate matter, and no need to dispose of radioactive waste materials.

There are, however, certain impacts that must be considered and managed if geothermal energy, including EGS, is to be developed as a larger part of a more environmentally sound, sustainable energy portfolio for the future. Most of the potentially important environmental impacts of geothermal power plant development are associated with ground water use and contamination, and with related concerns about land subsidence and induced seismicity as a result of water injection and production into and out of a fractured reservoir formation. Issues of air pollution, noise, safety, and land use also merit consideration.

The next section presents a comprehensive overview of environmental issues, summarizes the body of experience from hydrothermal plants, contrasts geothermal operations with alternative systems, and estimates the impact from EGS operations.

8.2 Potential Environmental Impacts from Geothermal Development

8.2.1 Gaseous emissions

Gaseous emissions result from the discharge of noncondensable gases (NCGs) that are carried in the source stream to the power plant. For hydrothermal installations, the most common NCGs are carbon dioxide (CO_2) and hydrogen sulfide (H_2S), although species such as methane, hydrogen, sulfur dioxide, and ammonia are often encountered in low concentrations. In the United States, emissions of H_2S – distinguished by its "rotten egg" odor and detectable at 30 parts per billion – are strictly regulated by the Environmental Protection Agency (EPA) to avoid adverse impacts on plant and human life. We expect that for most EGS installations, there will be lower amounts of dissolved gases than are commonly found in hydrothermal fluids. Consequently, impacts would be lower and may not even require active treatment and control. Nonetheless, for completeness, we review here the situation encountered today for managing gaseous emissions from hydrothermal plants.

Emissions are managed through process design. In steam and flash plants, naturally occurring NCGs in the production fluid must be removed to avoid the buildup of pressure in the condenser and the resultant loss in power from the steam turbine (see Figures 7.5 and 7.6). The vent stream of NCGs can be chemically treated and/or scrubbed to remove H_2S, or the NCGs can be recompressed and injected back into the subsurface with the spent liquid stream from the power plant. Both of these solutions require power, thereby increasing the parasitic load and reducing the plant output and efficiency. Binary plants avoid this problem because such plants only recover heat from the source fluid stream by means of a secondary working fluid stream. The source geofluid stream is reinjected without releasing any of the noncondensables.

The selection of a particular H_2S cleanup process from many commercially available ones will depend on the specific amounts of contaminants in the geofluid stream and on the established gaseous emissions standards at the plant site.

So far in the United States, there are no standards to be met for the emission of CO_2 because the United States has not signed the Kyoto agreement. Nevertheless, geothermal steam and flash plants emit much less CO_2 on an electrical generation basis (per megawatt-hour) than fossil-fueled power plants, and binary plants emit essentially none. The concentrations of regulated pollutants – nitrogen oxide (NOx) and sulfur dioxide (SO_2) – in the gaseous discharge streams from geothermal steam and flash plants are extremely minute. Table 8.1 shows a comparison of typical geothermal plants with other types of power plants (Kagel et al., 2005).

The data indicate that geothermal plants are far more environmentally benign than the other conventional plants. It should be noted that the NOx at The Geysers comes from the combustion process used to abate H_2S in some of the plants; most geothermal steam plants do not rely on combustion for H_2S abatement and therefore emit no NOx at all.

Table 8.1 Gaseous emissions from various power plants.

Plant type	CO_2 kg/MWh	SO_2 kg/MWh	NO_x kg/MWh	Particulates kg/MWh
Coal-fired	994	4.71	1.955	1.012
Oil-fired	758	5.44	1.814	N.A.
Gas-fired	550	0.0998	1.343	0.0635
Hydrothermal – flash-steam, liquid dominated	27.2	0.1588	0	0
Hydrothermal – The Geysers dry steam field	40.3	0.000098	0.000458	negligible
Hydrothermal – closed-loop binary	0	0	0	negligible
EPA average, all U.S. plants	631.6	2.734	1.343	N.A.

N.A. = not available

8.2.2 Water pollution

Liquid streams from well drilling, stimulation, and production may contain a variety of dissolved minerals, especially for high-temperature reservoirs (>230°C). The amount of dissolved solids increases significantly with temperature. Some of these dissolved minerals (e.g., boron and arsenic) could poison surface or ground waters and also harm local vegetation. Liquid streams may enter the environment through surface runoff or through breaks in the well casing. Surface runoff is controlled by directing fluids to impermeable holding ponds and by injection of all waste streams deep underground. To guard against fluids leaking into shallow fresh-water aquifers, well casings are designed with multiple strings to provide redundant barriers between the inside of the well and the adjacent formation. Nevertheless, it is important to monitor wells during drilling and subsequent operation, so that any leakage through casing failures can be rapidly detected and managed.

In principle, EGS operations are subject to the same possibility for subsurface contamination through casing defects, but there is little chance for surface contamination during plant operation because all the produced fluid is reinjected. Of course, a catastrophic failure of a surface pipeline could lead to contamination of a limited area until isolation valves are activated and seal off the affected pipeline.

8.2.3 Solids emissions

There is practically no chance for contamination of surface facilities or the surrounding area by the discharge of solids *per se* from the geofluid. The only conceivable situation would be an accident associated with a fluid treatment or minerals recovery system that somehow failed in a catastrophic manner and spewed removed solids onto the area. There are no functioning mineral recovery facilities of this type at any geothermal plant – although one was piloted for a short time near the Salton Sea in southern California – and it is not envisioned that any such facility would be associated with an EGS plant. Precautions, however, would need to be in place should the EGS circulating fluid require chemical treatment to remove dissolved solids, which could be toxic and subject to regulated disposal and could plug pathways in the reservoir.

8.2.4 Noise pollution

Noise from geothermal operations is typical of many industrial activities (DiPippo, 1991a). The highest noise levels are usually produced during the well drilling, stimulation, and testing phases when noise levels ranging from about 80 to 115 decibels A-weighted (dBA) may occur at the plant fence boundary. During normal operations of a geothermal power plant, noise levels are in the 71 to 83 decibel range at a distance of 900 m (DiPippo, 2005). Noise levels drop rapidly with distance from the source, so that if a plant is sited within a large geothermal reservoir area, boundary noise should not be objectionable. If necessary, noise levels could be reduced further by the addition of mufflers or other soundproofing means but at added cost. For comparison, congested urban areas typically have noise levels of about 70 to 85 decibels, and noise levels next to a major freeway are around 90 decibels. A jet plane just after takeoff produces noise levels of about 120 to 130 decibels.

During normal operations, there are three main sources of noise: the transformer, the power house, and the cooling tower. Because the latter is a relatively tall structure and the noise emanates from the fans that are located at the top, these can be the primary source of noise during routine operation. Air-cooled condensers employ numerous cells, each fitted with a fan, and are worse from a noise perspective than water cooling towers, which are smaller and use far fewer cells for a given plant rating.

Because EGS plants will likely be located in regions where water may be in short supply, they may require air-cooling, and proper attention may be needed to muffle the sound from their air-cooled condensers.

8.2.5 Land use

Land footprints for hydrothermal power plants vary considerably by site because the properties of the geothermal reservoir fluid and the best options for waste stream discharge (usually reinjection) are highly site-specific. Typically, the power plant is built at or near the geothermal reservoir because long transmission lines degrade the pressure and temperature of the geofluid. Although well fields can cover a considerable area, typically 5 to 10 km^2 or more, the well pads themselves will only cover about 2% of the area. With directional-drilling techniques, multiple wells can be drilled from a single pad to minimize the total wellhead area.

Gathering pipelines are usually mounted on stanchions, so that most of the area could be used for farming, pasture, or other compatible use (see Figure 8.1). The footprint of the power plant, cooling towers, and auxiliary buildings and substation is relatively modest. Holding ponds for temporary discharges (during drilling or well stimulation) can be sizeable but represent only a small fraction of the total well field.

Figure 8.1 Typical pipeline at Miravalles geothermal power plant, Costa Rica (photo by R. DiPippo).

A comparison of land uses for typical geothermal flash and binary plants with those of coal and solar photovoltaic plants is presented in Table 8.2 using data from DiPippo (1991b).

Table 8.2 Comparison of land requirements for typical power generation options.

Technology	Land use m^2/MW	Land use m^2/GWh
110 MW geothermal flash plant (excluding wells)	1,260	160
20 MW geothermal binary plant (excluding wells)	1,415	170
49 MW geothermal FC-RC plant (1) (excluding wells)	2,290	290
56 MW geothermal flash plant (including wells, (2) pipes, etc.)	7,460	900
2,258 MW coal plant (including strip mining)	40,000	5,700
670 MW nuclear plant (plant site only)	10,000	1,200
47 MW (avg) solar thermal plant (Mojave Desert, CA)	28,000	3,200
10 MW (avg) solar PV plant(3) (Southwestern US)	66,000	7,500

(1) Typical Flash-Crystallizer/Reactor-Clarifier plant at Salton Sea, Calif.

(2) Wells are directionally drilled from a few well pads.

(3) New land would not be needed if, for example, rooftop panels were deployed in an urban setting.

These data incorporate realistic capacity factors for each technology. Note that average power outputs, not rated values, were used for the solar plants. A solar-thermal plant requires about 20 times more area than a geothermal flash or binary plant; and a solar photovoltaic plant (in the best insolation area in the United States) requires about 50 times more area than a flash or binary plant per MW. The ratios are similar on a per MWh basis. The coal plant, including 30 years of strip mining, requires between 30-35 times the surface area for a flash or binary plant, on either a per MW or MWh basis. The nuclear plant occupies about seven times the area of a flash or binary plant. The land use for geothermal plants having hypersaline brines is about 75% greater than either simple flash or binary because of the large vessels needed to process the brine.

EGS plants are expected to conform more closely to the conventional geothermal flash and binary plants because of the relatively benign chemical nature of the circulating fluids. See Section 8.2.11 for further discussion of land use.

8.2.6 Land subsidence

If geothermal fluid production rates are much greater than recharge rates, the formation may experience consolidation, which will manifest itself as a lowering of the surface elevation, i.e., this may lead to surface subsidence. This was observed early in the history of geothermal power at the Wairakei field in New Zealand where reinjection was not used. Subsidence rates in one part of the field were as high as 0.45 m per year (Allis, 1990). Wairakei used shallow wells in a sedimentary basin. Subsidence in this case is very similar to mining activities at shallow depths where raw minerals are extracted, leaving a void that can manifest itself as subsidence on the surface. After this experience, other geothermal developments adopted actively planned reservoir management to avoid this risk.

Most of EGS geothermal developments are likely to be in granitic-type rock formations at great depth, which may contain some water-filled fractures within the local stress regime at this depth. After a geothermal well is drilled, the reservoir is stimulated by pumping high-pressure water down the well to open up existing fractures (joints) and keep them open by relying on the rough surface of the fractures. Because the reservoir is kept under pressure continuously, and the amount of fluid in the formation is maintained essentially constant during the operation of the plant, the usual mechanism causing subsidence in hydrothermal systems is absent and, therefore, subsidence impacts are not expected for EGS systems.

8.2.7 Induced seismicity

Induced seismicity in normal hydrothermal settings has not been a problem because the injection of waste fluids does not require very high pressures. However, the situation in the case of many EGS reservoirs will be different and requires serious attention. Induced seismicity continues to be under active review and evaluation by researchers worldwide. Annual workshops have been held recently to discuss current results (see, e.g., Majer and Baria, 2006).

The process of opening fractures can occur in a sliding manner by shear failure or in extensional manner by tensile failure. In either case, acoustic noise is generated during this process. This acoustic noise is referred to as microseismic noise or events. The acoustic noise is monitored during the stimulation process as an EGS reservoir management tool to see how far the stimulation has opened the reservoir in three dimensions (Batchelor et al., 1983; Baria et al., 1985; Baria and Green, 1989; Baria et al., 1995; Baria, 1990; Baria et al., 2005; Baria et al., 2006). This is analogous to tracking a submarine through acoustic noise patterns. The microseismic monitoring pinpoints how the pressure waves are migrating in the rock mass during the reservoir creation process. In the EGS systems studied to date (see Chapter 4) shear failure has been the dominant mechanism.

Signatures of the microseismic events also can be used to quantify the energy radiated from the shearing of fractures, the size of the fractures, the orientation of fractures, dilation and slip of fractures, etc. This is a unique method and serves as a remote sensing technique to observe changes in the reservoir properties (stress), not just during the development of the reservoir but also during the long-term energy-extraction phase.

Typically, natural fractures vary in length on a scale of 1 to 10 meters. Seismic energy radiated during the shearing process depends on the length of the fracture or the stress release from the constraining natural forces. A majority of the observed data from existing EGS projects suggest that the higher energy radiated from the shearing is caused by a high stress release from relatively small joint lengths (Michelet et al., 2004). This would suggest that if there were some perceived events on the surface, the frequency content would be too high to generate any seismic risk, but minor events may still raise concerns among local inhabitants.

Experience to-date suggests that an appropriate infrastructure needs to be set up to inform local residents about the program prior to the implementation of an EGS project. Planning needs to include a system where local residents are briefed on the project and are encouraged to contact a specified person on the program whose duties include answering questions and dealing responsively and sympathetically to any concerns of the local residents. Regular public meetings and arranged visits to the site from schools and interested parties are a way of enhancing acceptance of the program by local residents.

The collection of baseline data at the selected site prior to the onset of drilling is useful in separating natural from induced events. Additionally, it is prudent to instrument the site for any unexpected natural or induced felt microseismic events. A procedure also needs to be in effect to assess any effects on the public and local infrastructure. Lastly, sound geological and tectonic investigations must be carried out prior to the selection of the site to avoid the inadvertent lubrication of a major fault that could cause a significant seismic event.

8.2.8 Induced landslides

There have been instances of landslides at geothermal fields. The cause of the landslides is often unclear. Many geothermal fields are in rugged terrain that is prone to natural landslides, and some fields actually have been developed atop ancient landslides. Some landslides can be triggered by large earthquakes, but it is highly unlikely that geothermal production and injection could lead to such a massive event. Badly sited wells, particularly shallow injection wells, may interact with faults and cause slippage similar to what has been described in the preceding section.

Under these circumstances, it is possible for a section of a slope to give way initiating a landslide. However, such events at hydrothermal fields are rare, and proper geological characterization of the field should eliminate the possibility of such a catastrophe. EGS reservoir development should avoid areas of high landslide risk even though the chance of a catastrophic event is extremely low.

8.2.9 Water use

Geothermal projects, in general, require access to water during several stages of development and operation. Water use can be managed in most cases to minimize environmental impacts. Various aspects of water use in EGS projects are described below.

Well drilling, reservoir stimulation, and circulation. Water is required during well drilling to provide bit cooling and rock chip removal. This water (actually a mixture of water and chemicals) is recirculated after being cooled and strained. Makeup water is required to compensate for evaporation losses during cooling.

It is expected that in most advanced EGS applications, surface water will be needed to both stimulate and operate the reservoir (i.e., the underground heat exchanger) and produce the circulation patterns needed. The quantity of hydrothermal fluids naturally contained in the formation is likely to be very limited, particularly in formations with low natural permeability and porosity. In the western part of the United States, where water resources are in high demand, water use for geothermal applications will require careful management and conservation practice. The water may be taken from a nearby high-flow stream or river, if available, or collected in a temporary surface reservoir during the rainy season. Sometimes, local streams may be dammed and diverted. In some EGS resource areas, water treatment will be needed to ensure sufficient quality for reinjection and reuse or to remove potentially hazardous contaminants that might be dissolved or suspended in the circulating geofluid or cooling water. It is necessary to coordinate water use during field development with other local water demands for agricultural or other purposes.

Fluids produced from the reservoir. Production of geofluids from a hydrothermal reservoir for use in power or thermal energy generation can lower the water table, adversely affect nearby geothermal natural features (e.g., geysers, springs, and spas), create hydrothermal (phreatic) eruptions, increase the steam zone, allow saline intrusions, or cause subsidence. EGS systems are designed to avoid these impacts by balancing fluid production with recharge. In principle, EGS systems may be approximated as "closed-loop" systems whereby energy is extracted from the hot fluid produced by production wells (namely, a heat exchanger for binary plants) and cooled fluid is reinjected through injection wells. However, the circulation system is not exactly closed because water is lost to the formation; this lost water must be made up from surface water supplies.

Cooling water for heat rejection. Cooling water is generally used for condensation of the plant working fluid. The waste heat can be dissipated to the atmosphere through cooling towers if makeup water is available. Water from a nearby river or other water supply can also serve as a heat sink. There are opportunities for recovering heat from these waste fluids (and possibly from the brine stream) in associated activities such as fish farms or greenhouses.

An alternative to water-cooling is the technique of air-cooling using electric motor-driven fans and heat exchangers. This approach is particularly useful where the supply of fresh water is limited, and is currently used mainly for binary power plants (see Chapter 7). While air-cooled condensers eliminate the need for fresh makeup water that would be required for wet cooling towers, they occupy large tracts of land owing to the poor heat transfer properties of air vs. water. This greatly increases the land area needed for heat rejection compared to a plant of the same power rating that uses a wet cooling tower. For example, in the case of the 15.5 MW bottoming binary plant at the Miravalles field in Costa Rica, a design comparison between a water-cooling tower and an air-cooled condenser showed that the air-cooled condenser would cost more than three times as much, weigh more than two-and-a-half times as much, cover about three times as much surface area, and consume about three times more fan power than a water-cooling tower (Moya and DiPippo, 2006).

The environmental impacts of waste heat rejection into the atmosphere or water bodies can be minimized through intelligent design and the use of well-developed technologies; but the amount of heat that must be dissipated is controlled by the laws of thermodynamics.

8.2.10 Disturbance of natural hydrothermal manifestations

Although numerous cases can be cited of the compromising or total destruction of natural hydrothermal manifestations such as geysers, hot springs, mud pots, etc. by geothermal developments (Jones, 2006; Keam et al., 2005), EGS projects will generally be sited in non-hydrothermal areas and will not have the opportunity to interfere with such manifestations. For EGS facilities sited at the margins of existing hydrothermal plants where manifestations might be present, reservoir simulations should be performed to gauge the possible effects on those surface thermal features of drilling new wells and operating the EGS plant. However, because there is no “drawdown” in the traditional sense of an existing water table for an EGS system, it is unlikely that normal operations will have a significant effect on them.

8.2.11 Disturbance of wildlife habitat, vegetation, and scenic vistas

Problems related to loss of habitat or disturbance of vegetation are relatively minor or nonexistent at hydrothermal projects in the United States. Given the relatively small area taken out of the environment for geothermal operations, these potential impacts can be minimized with proper planning and engineering. It is difficult to imagine an EGS development causing more of an impact on wildlife and vegetation than a hydrothermal project. Furthermore, an Environmental Impact Statement must be filed before any permits can be granted for a geothermal project, and any potential impact in this area would have to be addressed.

It is undeniable that any power generation facility constructed where none previously existed will alter the view of the landscape. Urban plants, while objectionable to many for other reasons, do not stand out as abruptly as a plant in a flat agricultural region or one on the flank of a volcano. Many geothermal plants are in these types of areas, but with care and creativity can be designed to blend into the surroundings. Avoiding locations of particular natural beauty is also important, whether or not the land is nationally or locally protected. EGS developments will be no different than conventional hydrothermal plant developments, in that the design of the facility must comply with all local siting requirements.

The development of a geothermal field can involve the removal of trees and brush to facilitate the installation of the power house, substation, well pads, piping, emergency holding ponds, etc. However, once a geothermal plant is built, reforestation and plantings can restore the area to a semblance of its original natural appearance, and can serve to mask the presence of buildings and other structures. For example, Figures 8.2 and 8.3 show the Ahuachapán geothermal facility in El Salvador, soon after commissioning around 1977 (DiPippo, 1978), and then after regrowth of trees and vegetation in 2005 (LaGeo, 2005).

Figure 8.2 Ahuachapan geothermal facility after commissioning around 1977 (DiPippo, 1978).

Figure 8.3 Ahuachapan geothermal facility after revegetation, circa 2005 (LaGeo, 2005).

Geothermal plants generally have a low profile and are much less conspicuous than, for example, wind turbines, solar power towers, or coal plants with chimneys as tall as 150-200 m. Buildings and pipelines can be painted appropriate colors to help conceal them from a distance. While it is impossible to conceal steam being vented from flash plants – a periodic occurrence during normal operation – most people do not object to the sight of white steam clouds in the distance. Binary plants during normal operation have no emissions whatsoever.

There are several geothermal power plants in the Imperial Valley of California that coexist harmoniously with various agricultural activities. Figure 8.4 shows an aerial view of the 40 MW SIGC Heber binary plant amid fields of alfalfa in California's Imperial Valley (Google Earth, 2006). Notice that the plant site, including the main production well pad, covers about 0.12 km^2 or about 3,000 m^2/MW. The power plant proper, excluding the wells, covers only 0.041 km^2 or about 1,020 m^2/MW. The barren land to the south of the plant site was the location of an older experimental binary plant that has been decommissioned (DiPippo, 2005).

Figure 8.4 Aerial view of the SIGC binary plant near Heber, Calif. (Google Earth, 2006).

Figure 8.5 is a view of the 47 MW Heber Double-Flash plant that is located just to the east of the SIGC plant. The area occupied by this plant and all well pads and holding ponds is about 0.095 km^2 or about 2,000 m^2/MW. Both of these plants illustrate how geothermal plants, flash and binary, can operate compatibly within an agricultural environment and be economical of land space.

With regard to the construction of an EGS facility, it can be expected that similar impacts will take place on the land surface and result in a facility having a central power plant with a network of above-ground pipelines connecting the power station to a set of production and injection wells. However, the land can be at least partially restored to its natural condition through the same reclamation techniques practiced at hydrothermal plants.

Figure 8.5 Aerial view of the Heber Double-Flash plant, Calif. (Google Earth, 2006).

8.2.12 Catastrophic events

Accidents can occur during various phases of geothermal activity including well blowouts, ruptured steam pipes, turbine failures, fires, etc. This is no different from any other power generation facility where industrial accidents unfortunately can and do happen. The ones that are unique to geothermal power plants involve well drilling and testing. In the early days of geothermal energy exploitation, well blowouts were a fairly common occurrence; but, nowadays, the use of sophisticated and fast-acting blowout preventers have practically eliminated this potentially life-threatening problem. Furthermore, geothermal prospects are now more carefully studied using modern geoscientific methods before well drilling commences.

In the case of EGS projects, it will be critical to study and characterize the nature of any potential site before any development begins. This will minimize the chances for a catastrophic event related to the drilling phase. Proper engineering and adherence to standard design codes should also minimize, if not completely eliminate, any chance of a mechanical or electrical failure that could cause serious injury to plant personnel or local inhabitants.

8.2.13 Thermal pollution

Although thermal pollution is currently not a specifically regulated quantity, it does represent an environmental impact for all power plants that rely on a heat source for their motive force. Heat rejection from geothermal plants is higher per unit of electricity production than for fossil fuel plants or nuclear plants, because the temperature of the geothermal stream that supplies the input thermal energy is much lower for geothermal power plants. Considering only thermal discharges at the plant site, a geothermal plant is two to three times worse than a nuclear power plant with respect to thermal pollution, and the size of the waste heat rejection system for a 100 MW geothermal plant will be about the same as for a 500 MW gas turbine combined cycle (DiPippo, 1991a). Therefore, cooling towers or air-cooled condensers are much larger than those in conventional power plants of the same electric power rating. The power conversion systems for EGS plants will be subject to the same laws of thermodynamics as other geothermal plants, but if higher temperature fluids can be generated, this waste heat problem will be proportionally mitigated.

8.3 Environmental Attributes of EGS Power Projects

8.3.1 No greenhouse gas emissions during operations

Geothermal power plants built on EGS reservoirs and using "closed-loop" cycles will emit no carbon dioxide (CO_2), one of the principal greenhouse gases (GHGs) implicated in global warming. Although not currently a signatory to the Kyoto agreement, the United States may find itself forced to address this problem soon. A decision by the U.S. Supreme Court is expected by June 2007, which could lead to a new posture by the government on CO_2 emissions. If a "carbon tax" were to be implemented, the cost to generate a kilowatt-hour of electricity from fossil-fueled plants would increase relative to other less-polluting technologies. EGS plants would not be penalized and could gain an economic advantage over all plants using carbon-based fuels. If a program of "carbon credits" were to be established, EGS plants would gain an additional revenue stream by selling such credits on the carbon-credit trading market.

8.3.2 Modest use of land

In comparison with fossil-fueled, nuclear, or solar-electric power plants, EGS plants require much less land area per MW installed or per MWh delivered. In fact, the land required is not completely occupied by the plant and the wells, and can be used, for example, for farming and cattle-raising. The practice of directionally drilling multiple wells from a few well pads will keep the land use to a minimum. Furthermore, because EGS plants are not necessarily tied to hydrothermal areas, it may be possible to site them within populated and industrial districts, a clear advantage over fossil or nuclear plants.

8.3.3 Possible sequestration of carbon dioxide

Although not analyzed in this assessment, a proposal has been put forth to use CO_2 as the EGS reservoir heat-transfer fluid. Brown (2000) has developed a conceptual model for such a system based on the Fenton Hill Hot Dry Rock reservoir. The argument is made that CO_2 holds certain thermodynamic advantages over water in EGS applications. Based on the case study in his paper, a single EGS reservoir having a pore space of 0.5 km^3 could hold in circulation some 260 x 10^9 kg of CO_2, the equivalent of 70 years of CO_2 emissions from a 500 MW coal power plant having a capacity factor of 85%. EGS plants then could conceivably play a valuable symbiotic role in controlling CO_2 emissions while allowing the exploitation of the abundant supply of coal in the United States without contributing CO_2 to the atmosphere.

8.3.4 Low overall environment impact

In all aspects, with the exception of possible effects caused by induced seismicity, geothermal plants are the most environmentally benign means of generating base-load electricity. Overall, EGS plants would have comparable impact to hydrothermal binary plants operating with closed-loop circulation. The only potential area of concern, induced seismicity (which is somewhat unique to EGS), can be mitigated, if not overcome, using modern geoscientific methods to thoroughly characterize potential reservoir target areas before drilling and stimulation begin. Continuous monitoring of microseismic noise will serve not only as a vital tool for estimating the extent of the reservoir, but also as a warning system to alert scientists and engineers of the possible onset of a significant seismic event. On balance, considering all the technologies available for generating large amounts of electric power and their associated environmental impacts, EGS is clearly the best choice.

8.4 Environmental Criteria for Project Feasibility

In determining the feasibility of an EGS project at a particular location, there are a number of technical criteria that carry direct or indirect environmental implications:

- Electricity and/or heat demand in the region
- Proximity to transmission and distribution infrastructure
- Volume and surface expression of a high-quality EGS reservoir
- Reservoir life and replacement wells
- Circulating fluid chemistry
- Flash vs. binary technology
- Cost/installed MW_e and cost/MWh delivered to a local or regional market
- Load-following vs. base-load capability
- Plant reliability and safety.

In addition, as with any energy supply system, there are environmental criteria that need to be considered before moving forward with a commercial EGS project. These include:

- Geologic formations that are not prone to large seismic events, devastating landslides, or excessive subsidence
- Compatible land use
- Drinking water and aquatic life protection
- Air quality standards
- Noise standards
- GHG emissions/MWh
- Solid waste disposal standards
- Reuse of spent fluid and waste heat

- Acceptable local effects of heat rejection
- Compliance with all applicable federal, state, and local laws.

All of these will influence the acceptability and the cost of a project, and, ultimately, whether or not a project will go forward.

8.5 Concluding Remarks

Although there certainly are environmental impacts associated with EGS developments, they are generally more benign than those associated with other power generation technologies, particularly fossil and nuclear.

With more than 100 years of worldwide experience in geothermal operations including

- the design and operation of hydrothermal power plants, especially flash-steam and binary plants – the likely systems of choice for EGS power projects,
- geothermal well drilling,
- reservoir engineering and management, and
- abatement systems to mitigate environmental impacts,

future EGS power plant facilities can be designed and operated to have relatively small impacts on the local and regional environment. In fact, because EGS plants have a small footprint and can operate essentially emissions-free, the overall environmental impact of EGS power facilities is likely to be *positive*, reducing the growth of greenhouse gas emissions while providing a reliable and safe source of electricity.

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