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Environmental aspects of geothermal energy utilization

Hrefna Kristmannsdóttir*[,a], Halldór Ármannsson[b]

[a]University of Akureyri, Faculty of Natural Resource Sciences, Solborg, 600 Akureyri, Iceland
[b]Iceland Geosurvey, Grensásvegus 9, 108 Reykjavík, Iceland

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Abstract

Geothermal energy is a clean and sustainable energy source, but its development still has some impact on the environment. The positive and negative aspects of this environmental impact have to be considered prior to any decision to develop a geothermal field, as well as possible mitigation measures. The main environmental effects of geothermal development are related to surface disturbances, the physical effects of fluid withdrawal, heat effects and discharge of chemicals. All these factors will affect the biological environment as well. As with all industrial activities, there are also some social and economic effects. In Iceland an enforcement program was launched in the early 1990s to study the environmental impact of developing geothermal resources. Work began on tackling the environmental issues relative to the high-temperature geothermal fields under development in Iceland. Research was conducted on microearthquake activity in geothermal areas and a methodology developed for mapping steam caps. The foundations were laid of networks for monitoring land elevation and gravity changes. Baseline values were defined for the concentrations of mercury and sulfur gases. Groundwater monitoring studies were enforced. Atmospheric dispersion and reaction of geothermally-emitted sulfur gases and mercury were studied. Aerial thermographic survey methods were refined and tested and their capacity to detect and map changes in surface manifestations with time was demonstrated. To further the use of geothermal energy worldwide the International Energy Association set up a Geothermal Implement Agreement (GIA) in 1997; its environmental Annex has been actively implemented, with several projects still under way.

Keywords: Environment; Geothermal development; Natural changes; Mitigation; Gas emissions

* Corresponding author. Fax: +354-568-8896.
E-mail address: hk@os.is (H. Kristmannsdóttir).

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1. Introduction

All energy production causes some changes to the environment and requires some kind of engineering and building activity, which induces environmental effects of some kind. Although geothermal energy is considered to be a clean energy source, its development will lead to some emission of gases and effluent water that require disposal. Compared to nuclear and fossil fuels, geothermal is a benign energy source. The relative amounts of greenhouse gas emissions from electricity of geothermal origin are only a fraction of the amounts coming from fossil fuel, and are of the same magnitude as most other renewable energy sources, such as hydro and solar energy (Fig. 1). The geothermal electricity produced in the world in a year is estimated to be the equivalent to savings of 12.5 million tons (Mt) of fuel oil per year, whereas the savings due to direct geothermal heat use (and geothermal heat pumps) is equivalent to about 13.1 Mt per year (Hunt, 2001; Lund and Freeston, 2001). The corresponding savings in CO_2 emissions per year exceed 80 Mt. About 53% of the total energy consumed in Iceland is from geothermal energy whereas only 5% of the greenhouse gas emissions (in CO_2 equivalents) are from the production of geothermal energy (Ragnarsson, 2001; Hallsdóttir, 2001). For a long time now the effects of geothermal production on the environment have been studied, evaluated and compared with the effects of other forms of energy (Axtman, 1975; Ellis, 1975). The first Environmental Impact Assessment (EIA) was compiled in the USA in 1970 and since then many countries have set up their own procedures, usually referring to the 1987 report from the World Commission on Environment and Development and the 1992 United Nations Conference on Environment and

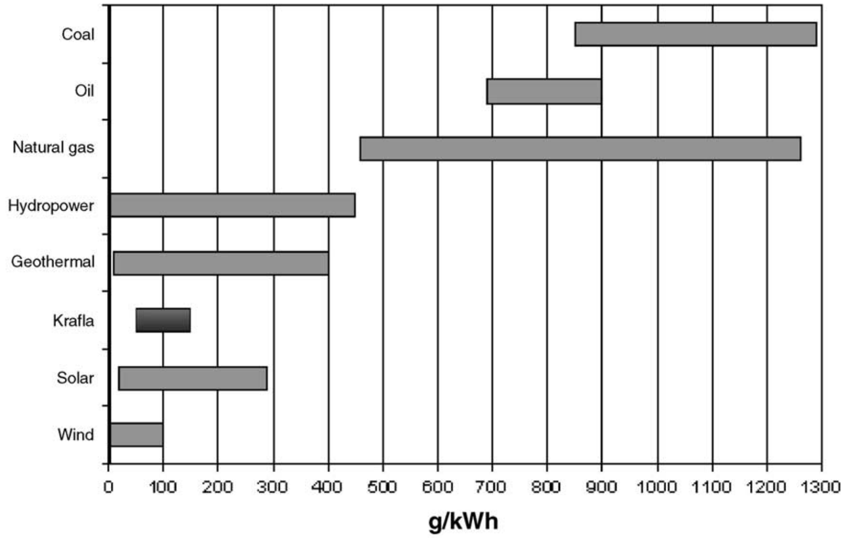

Fig. 1. Greenhouse gas emissions from various types of energy sources during generation of electricity. The emissions are expressed as CO_2 equivalents (Hunt, 2001; Ármannsson et al., 2001). Krafla has one of the highest CO_2 emissions of the Icelandic geothermal fields.

Development (Hongying, 2000) The techniques used vary but checklists of special factors that may be affected by development and matrices of various kinds are universally used and concern physical, socio-economic, chemical and biological impacts. The EIA process has proved to be a powerful tool for environmental safeguarding in geothermal project planning. Environmental effects vary considerably from one geothermal field and power plant to another, depending on the special characteristics of the field in question. In this respect the geology and structure of the underground as well as the type of reservoir play a major role. The type of utilization is obviously also of importance. All possible changes must be appraised in an environmental assessment report prior to exploitation and an optimum solution devised. In this respect it is of utmost importance to have knowledge of the natural behaviour of the area and monitoring of the field is needed several years prior to development (Kristmannsdóttir and Ármannsson, 1999; Ármannsson et al., 2000b).

2. Impact on the environment

The main environmental issues involved in geothermal development are:

- Surface disturbances
- Physical effects of fluid withdrawal
- Noise
- Thermal effects
- Chemical pollution
- Biological effects
- Protection of natural features

Surface disturbances may occur during drilling, but will mostly disappear once drilling is completed, the drill rigs have been removed, the ponds drained and the landscape reshaped. Surface disturbances caused by excavation, construction and the creation of new roads will accompany most new activities, but the area involved is relatively small. A drillsite usually covers 200–2500 m^2 and can be kept at a minimum by directional drilling of several wells from one site. As the source is normally utilized near the drillsite there is no need for long pipelines. Space heating is an exception to this general rule as the pipelines in this case could be quite long.

Landslides are liable to occur in some places and may set constraints on the sites chosen for construction. As geothermal fields are often associated with volcanic rocks such as pumice and the soil and upper basement in geothermal fields are often thermally altered and can become increasingly so during utilization, the landslide factor has to be carefully monitored. There are several examples of bad landslides that were directly connected with the installation of geothermal plants (Goff and Goff, 1997).

The *scenery* needs attention, as geothermal fields are often situated in places of outstanding beauty and touristic importance and may also be of historic interest. There are, however, many examples of the beneficial effects of utilization to tourism, as an added attraction. One of the most striking is the Blue Lagoon in the Svartsengi high-temperature field, which is now one of Iceland's most renowned tourist landmarks, but is actually an effluent pond that accidentally became far larger than was originally anticipated. It is worth pondering that a licence to dump the water in this way would certainly not be issued today.

Fluid withdrawal can effect *changes to surface manifestations*, causing hot springs or geysers to disappear or be transformed into fumaroles; the site of this type of activity could even shift to another area.

Untidiness can lead to unacceptable eyesores and it should be a feature of any monitoring program that the sites be inspected by an outside agency.

Physical effects are induced by the fluid withdrawal that accompanies the utilization of geothermal resources. Fluid withdrawal can cause land subsidence, lowering of the groundwater table and even induced seismicity.

Subsidence takes place when fluid withdrawal exceeds the natural inflow. There is evidence in almost every utilized area, although the magnitude of this phenomenon can vary greatly. In Wairakei, New Zealand, the maximum subsidence is 15 m (400 mm/year), whereas in Svartsengi, Iceland, the total subsidence is less than 28 cm (10 mm/year, Fig. 2). In Larderello, Italy, subsidence lies somewhere between these two figures (250 mm/year) (Hunt, 2001; Allis, 2000; Eysteinsson, 2000; Aust and Sustrac, 1992).

Lowering of the groundwater table may cause mixing of fluids between aquifers and an inflow of corrosive water. It may also cause the disappearance of springs and

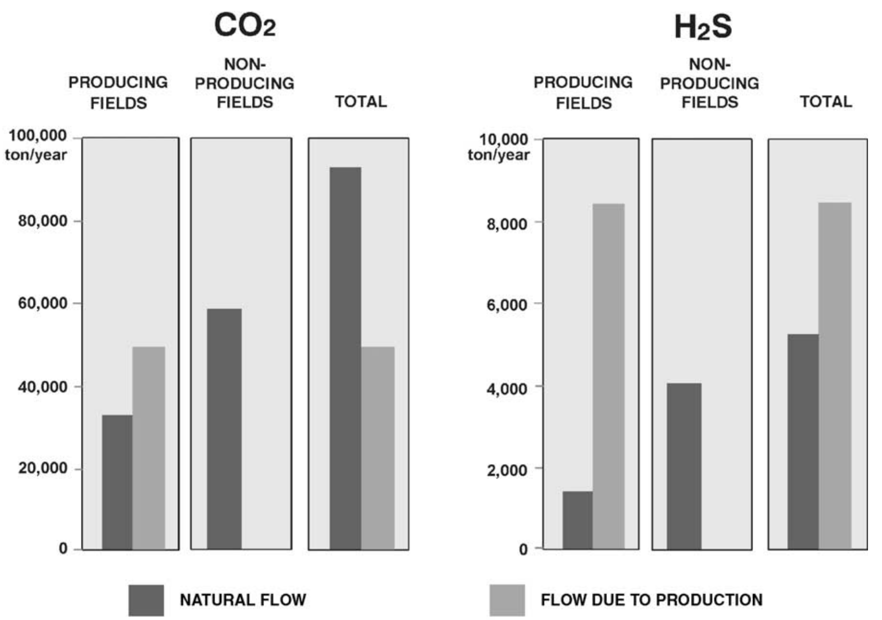

Fig. 2. CO_2 and H_2S emissions from Icelandic geothermal fields (Ármannsson et al., 2001).

fumaroles or changes in surface activity (Glover et al., 2000). Lowering of the groundwater table can also lead to the formation or accelerated growth of a *steam pillow* and subsequent boiling and degassing of the field. Such a development may induce major explosions that have in the past killed a number of people (Hunt, 2001; Goff and Goff, 1997). The effects of fluid withdrawal can to a large extent be overcome by injecting the spent fluid back into the reservoir.

The natural *seismicity* may also be changed by fluid withdrawal, as observed in Svartsengi (Brandsdóttir et al., 2002). Reinjection may also induce microseismicity (Hunt, 2001).

The *noise* brought on by geothermal utilization consists firstly of drilling noise, which is temporary and rarely exceeds 90 dB; this is followed by the noise from discharging boreholes, which may exceed 120 dB, the pain threshold ranging between 2 and 4000 Hz. Once the plant has started operations a noise muffler can keep the environmental noise below the 65 dB limit set by the US Geological Survey.

Heat-thermal effects and even pollution will normally accompany production from geothermal fields. The heat efficiency of power production is low, so a considerable amount of energy is wasted. Waste water causes problems for the environment. Excess heat emitted in the form of steam may affect cloud formation and change the weather locally, and waste water piped into streams, rivers, lakes or local groundwaters may seriously affect the biology and ecological system. Cooling in ponds can be achieved successfully and may even be beneficial to the environment, as in the case of the Blue Lagoon in Svartsengi, but it is generally not considered a good solution as the ponds tend to increase in size and may cause chemical pollution in the environment as well. Reinjection of spent fluid will save a considerable part of the waste heat. Multiple use of the resource is also a means of reducing the heat wastage. As demonstrated in the Lindal diagram, there are uses for the heat down to low temperatures (Lindal, 1973). Such multi-purpose plants have been designed and even put into operation in a number of areas. In cold regions like Iceland electricity and hot water are successfully co-generated and the heat is used for snow melting and ground heating after being used for house heating. In warm countries the excess heat could be used for air-cooling by means of heat pumps.

Chemical pollution in geothermal utilization is a result of the discharge of chemicals into the atmosphere via steam; the spent liquid may also contain dissolved chemicals of potential harm to the environment. Spray, which constitutes a problem mainly in the testing period, could damage vegetation in the surrounding area.

The main pollutant *chemicals in the liquid fraction* are hydrogen sulfide (H_2S), arsenic (As), boron (B), mercury (Hg) and other heavy metals such as lead (Pb), cadmium (Cd), iron (Fe), zinc (Zn) and manganese (Mn). Lithium (Li) and ammonia (NH_3), as well as aluminium (Al), may also occur in harmful concentrations. Some geothermal fluids are brines, whose excessive salt concentrations can cause direct damage to the environment.

Disposal of water of this type is a risky endeavour, as As and Hg, in particular, may accumulate in sediments and organisms. High concentrations of boron will also be a major concern as this element is very harmful to most plants. Effluent treatment is of course an option, but has seldom been considered economically viable. Ponding may reduce the pollution, but the most effective method for combatting water pollution is the reinjection of spent fluids.

Air pollution may be caused by the discharge of geothermal gases in the steam. The major offenders are carbon dioxide and hydrogen sulfide, although methane, mercury, radon, ammonia and boron can also cause problems. Carbon dioxide, which is usually the major constituent of the gas present in geothermal fluids, and methane, a minor constituent, both require attention because of their role as greenhouse gases. Following on the international convention in Rio in 1990, the industrialized nations are committed to reducing their production of greenhouse gases, although energy sources such as coal and oil are the main offenders in this respect. In a comparison of the CO_2 emitted from different types of power plant, the environmental benefits of replacing such plants with a geothermal plant are obvious (Fig. 1). Carbon dioxide production is already an industrial by-product in several geothermal plants, such as Kizildere, Turkey, thus reducing emissions even further. It has also been pointed out that the CO_2 emitted from geothermal plants is not created by power generation but is CO_2 that would have been vented out gradually through the earth anyway (Ármannsson et al., 2001). Research from volcanic terrains strongly suggests that the development of geothermal fields makes no difference to the total CO_2 emanated from those terrains (Bertani, 2001). Hydrogen sulfide probably causes the greatest concern as it has an unpleasant smell and is toxic in moderate concentrations. It has been observed that, as a result of geothermal field exploitation, the concentration of H_2S increases relatively more than the concentration of CO_2, probably because of the higher reactivity of H_2S. This is evident in the concentrations of the H_2S and CO_2 gas emanations from developed and non-developed geothermal fields in Iceland (Fig. 2). Complaints and reactions to the smell of H_2S vary considerably, depending on how much surface activity took place in the area beforehand. In some countries the removal of H_2S is mandatory. It is claimed that most of the H_2S will end up being oxidized to SO_2, and will thus add to the global acid rain problem, but the fate of the H_2S in the atmosphere is a matter of debate. Little evidence has been found of such an effect in the vicinity of power plants and it has not been demonstrated that the H_2S is indeed oxidized to SO_2 to any degree. On the contrary, it has been demonstrated that a considerable proportion of the H_2S is washed out of the steam and precipated as elemental sulfur. Research in Iceland on this issue strongly indicates that only a small fraction of the H_2S is oxidized to SO_2 in the climatic conditions of Iceland (Kristmannsdóttir et al., 2000b). Both carbon dioxide and hydrogen sulfide are heavy gases and tend to concentrate in pits and lows so careful monitoring is needed to ensure that hazardous conditions do not develop locally. Geothermal gases will also have an impact on the biology of an area (Webster and Timperley, 1995).

As many geothermal areas are of unique beauty, of historical interest or are tourist attractions, their *protection* must be considered. Disturbance to the natural state of an area can cause phenomena such as geysers, hot springs or pools, silica sinter terraces and mud pools, to deteriorate or disappear, along with special thermophilic vegetation such as algal mats, thermophilic plants and bacteria (Glover et al., 2000; Kristjansson and Stetter, 1992; Skirnisdottir et al., 2000; Marteinsson et al., 2001).

Besides the environmental effects discussed here, which are mostly physical, there are also *social and economical effects*. These may be considered in a positive or negative light, however, according to the political viewpoint of the individual, as in the case of any large-scale engineering project.

Generally there is a need for more *public involvement* in such issues as the construction of power plants, in order to resolve controversies, improve plans and take mitigation measures.

3. The Icelandic environmental project

In 1991 a co-operative project was launched by Orkustofnun (National Energy Authority) and the major high-temperature geothermal energy developers in Iceland (utilizing the Reykjanes, Svartsengi, Nesjavellir, Námafjall and Krafla fields). At that time a new environmental law was under preparation to establish and predict the environmental impact of geothermal utilization, and to suggest remedies. The first phase of the project was to assess the status in developed geothermal fields and to make recommendations for research and monitoring (Ármannsson and Kristmannsdóttir, 1992; Kristmannsdóttir and Ármannsson, 1995). During the next phase of the project several priority projects were defined (Kristmannsdóttir and Ármannsson, 1995; Kristmannsdóttir et al., 2000a):

- A survey of gas emissions from exploited geothermal fields, especially mercury and sulfur
- Investigation into the formation and pervasion of steam pillows in exploited fields
- Ground leveling and gravity measurements
- Groundwater monitoring
- Studies of the possible effects of development on microseismicity
- Aerial thermography as a means to monitor changes in geothermal activity
- Monitoring of non-developed areas for background comparison with developed areas
- Search for methods to measure natural steam discharges
- Evaluation methods for gas removal in power plants
- Studies of the environmental effects of reinjecting spent fluids
- Review of regulations for geothermal exploitation in other countries

The main effort was expended on the studies of gas emissions, ground leveling and gravity measurements, aerial thermography and on studies of non-developed areas. Studies of gas emissions entailed point measurements of the concentration of various gases in atmospheric air within a few geothermal fields, whether under exploitation or not (Fig. 3), followed by longer-term measurements of mercury, hydrogen sulfide (H_2S) and sulfur dioxide (SO_2) in selected geothermal fields (Bertani, 2001). The dispersion, decay and possible conversion with time of hydrogen sulfide to sulfur dioxide was monitored, suggesting that only a fraction of the H_2S dispersed from the geothermal fields is converted to SO_2 in the climatic conditions prevailing in Iceland.

Ground level and gravity measurements were carried out in all the developed high-temperature geothermal fields in Iceland (Fig. 4) and a network set up to monitor future trends (Eysteinsson, 2000).

The aerial thermal scanning project consisted in the refinement of a new light-weight thermal scanner, mounted on a small aircraft, which can provide high-quality thermal images; studies were also made of the efficacy of repeated aerial surveys in detecting and mapping changes in surface temperature with time (Kristmannsdóttir et al., 2000a; Árnason, 1997).

Four non-utilized areas were selected as type localities, and a report drafted on the status of research in 28 non-utilized fields, with reference to an EIA assessment for a 20 MW power plant (Kristmannsdóttir and Ármannsson, 1999; Ármannsson et al., 2000b). The enforcement project was officially terminated at the end of 1997, but work on many of the priority proects, such as the groundwater studies in the Mývatn region near to the Krafla and Námafjall geothermal fields (Ármannsson et al., 2000a) continued, in some cases, for five more years.

4. Geothermal implement agreement

In order to promote the utilization of geothermal energy, the International Energy Association set up a Geothermal Implement Agreement (GIA) in 1997; one of the

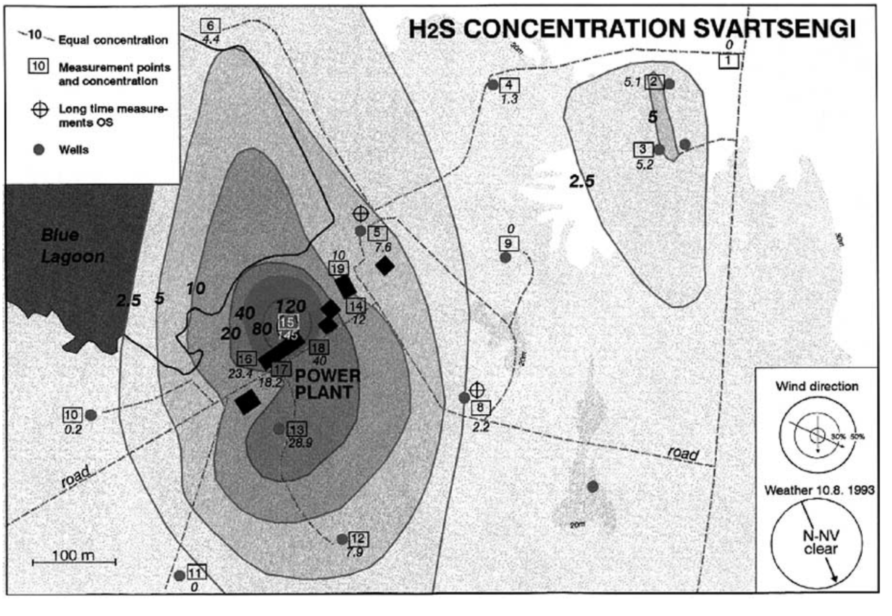

Fig. 3. The concentration of H_2S in μg/m^3 in air around the Svartsengi power plant, SW Iceland.

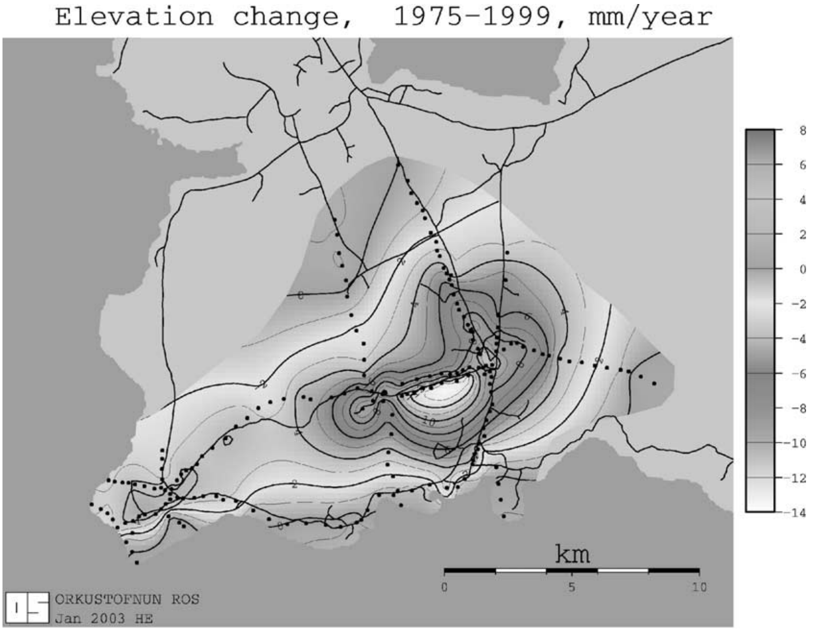

Fig. 4. Changes in elevation (mm/year) in the Reykjanes peninsula due to production in the Svartsengi (middle) and Reykjanes (tip of the peninsula) geothermal fields (Eysteinsson, 2000).

tasks of this Agreement was the study of the Environmental Impacts of Geothermal Energy Development, comprising Annex I of the GIA. The goals of this task are: to encourage the sustainable development of geothermal energy resources in an economic and environmentally responsible manner; to quantify any adverse or beneficial impacts that geothermal energy development may have on the environment, and to identify ways of avoiding, remedying or mitigating such adverse effects.

By early 2002, six countries were formally participating in this task: Greece, Iceland, Japan, Mexico, New Zealand, and the USA. Turkey is also expected to join, and active encouragement is being given to other geothermal countries to join the IEA-GIA agreement in future.

5. Future aspects

In a world that is showing an increasing concern for the environment, there is a greater emphasis on the utilization of clean and sustainable energy sources such as geothermal. The environmental effects of developing geothermal energy have still to be investigated in full, and a careful choice of power cycle and geothermal field has to be made. It is now generally acknowledged that geothermal fields have to be carefully monitored for several years prior to development in order to ensure the most viable field in environmental terms, as well as sustainable energy production and the least impact on the environmental in general.

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