Proceedings World Geothermal Congress 2020+1
Reykjavik, Iceland, April - October 2021

The Mapping of Geothermal Environmental Impacts and Risks in Iceland

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Keywords: geothermal, environmental, impact, risk, Iceland

ABSTRACT

The main objectives of this study is to map environmental impacts and risks, as well as their perception and to define how environmental footprint of deep geothermal plants in Europe is measured and controlled in different countries, and also analyze adopted solutions to reduce or circumvent impacts and risks, and quantify their potential and their technology readiness level.

In this communication the focus is on the experience of Iceland especially with Environmental Impact Assessments which were first made mandatory by Act N. 63/1993 on Environmental Impact Assessment but later amended by Act No. 106/2000.

The term "environmental impacts" refers to the following parameters.

- Landscape/scenery changes
- Effects on vegetation
- Effects on fauna
- Effects on surface water and ground water
- Effects on local climate
- Effects on tourism
- Effects on seismic activity
- Noise
- Gas emissions/Odor
- Socio/economic effects.

The following risks are considered most important in geothermal utilization and are treated in this communication.

- Landslides
- Steam pillow explosions
- Fracture movements
- Earthquakes
- Lava flows
- Gas collected in lows

1 INTRODUCTION

The study described here is a part of the preliminary work in the European Union project GEOENVI. The objective of the GEOENVI project is to answer environmental concerns in terms of both impacts and risks, by first setting an adapted methodology for assessing environment impacts to the project developers, and by assessing the environmental impacts and risks of geothermal projects operational or in development in Europe. It entails a documentation on environmental impacts and risks resulting in a database gathering information on environmental issues concerning European deep geothermal sites. In this paper the focus is on environmental impacts and risks connected with geothermal energy utilization in Iceland.

Fridleifsson (1979). considers that maximum temperatures are lower than about 150°C in the uppermost 1000 m of low-temperature areas, but reach at least 200°C in the uppermost 1000 m of high-temperature areas This division appears appropriate from a geological point of view. From the point of view of utilization, division of the present low-temperature areas into intermediate (90-150°C) and low-temperature (<90°C) ones would be feasible and in line with the definition adopted by the United Nations Environmental Programme (E1-Hinnawi, 1981). However, in the present paper the geological classification of Bödvarsson (1961) and Fridleifsson (1979) is used as a reference although uncertain areas whose temperatures at 1000 m depth might be in the range 150-200°C are included.

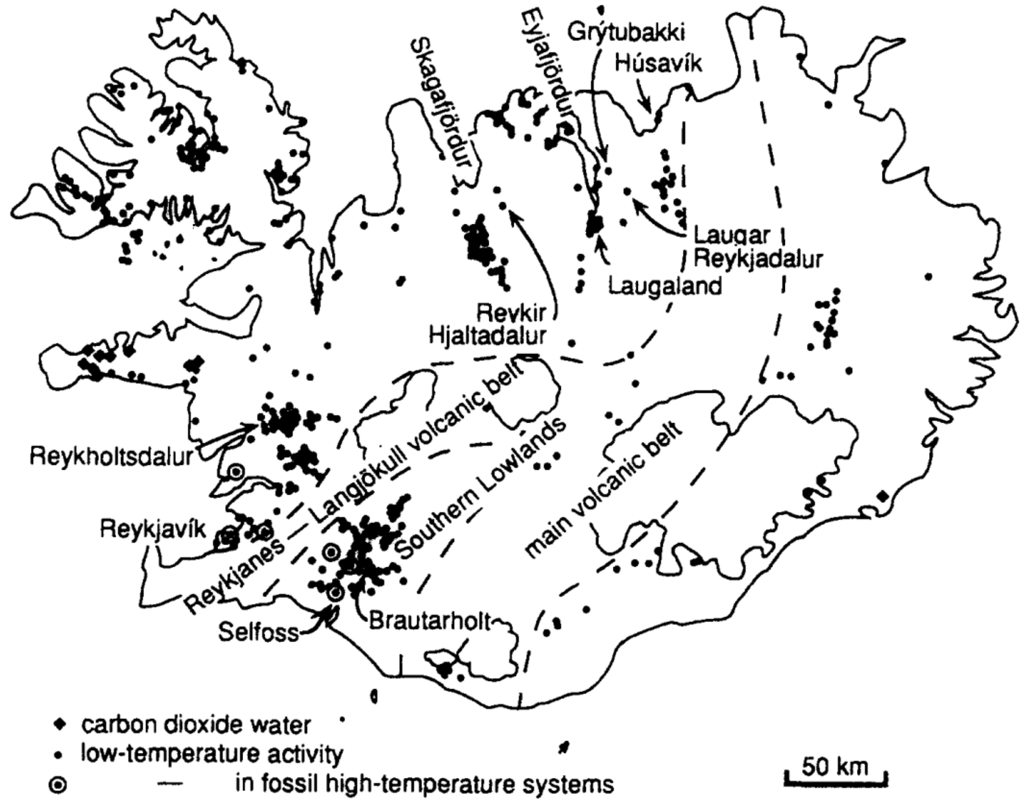

Figure 1: Distribution of low-temperature geothermal activity in Iceland

The low temperature areas of Iceland (Fig.1) have been described by Arnórsson (1995) and these are his main conclusions about their origins

(1) Deep flow of groundwater from highland to lowland areas through permeable structures driven by the hydraulic gradient.
(2) Convection in young fractures formed by tectonic movements in old and relatively impermeable bedrock.
(3) Drift of high-temperature geothermal systems out of the active volcanic belts in conjunction with their cooling and extinction of the magma heat source.
(4) Magma intrusion into young fractures in Quaternary and Tertiary formations close to the active volcanic belts´

The fluids of the low-temperature areas in Iceland are relatively low in dissolved solids. This is attributed to the low concentration of chloride in the basaltic rock, which forms soluble salts with the major aqueous cations. The dissolved solids concentration typically lies in the range of 150-500 ppm although it reaches several thousands of ppm in some coastal areas. Gases associated with these waters are largely N_2.. Oxygen is present in many warm waters (<50°C) as well as in some waters with temperatures up to 80°C.The pH of slightly thermal waters often exceeds 10, which is to be contrasted with a pH of 6-8 in surface waters. With increasing temperature above about 50°C the water pH tends to fall again and in the hottest (-150°C) waters it is 7-8.

The estimated total flow from natural springs is about 1800 l/s (Saemundsson and Fridleifsson, 1980). According to Pálmason *et al.* (1985) the natural power output in excess of 15°C is just over 500 MWt (megawatts thermal) corresponding to a weighted average temperature of 84°C. Almost two-thirds of the total heat output is limited to the three largest low-temperature areas, which are located in the southwestern part of the country on both sides of the Reykjanes-Langjökull active volcanic belt (Fig. 1). They include Reykholtsdalur with a natural discharge of 400 l/s (156 MWt), mostly of boiling water (Georgsson *et al.,* 1984), the Southern Lowlands with 350 I/s (122 MWt) (Arnórsson, 1970), of which 250 l/s are confined to 100 km 2 in Upper- Árnessýsla, and, finally, Mosfellssveit with natural flow rate of 120 l/s (44 MWt) according to Pálmason *et al.* (1985). Most of the low temperature activity takes place on the North-American lithospheric plate.

As the fluid is mostly rather benign and the nature of low temperature utilization does not cause great disturbances regarding scenery changes, noise and pollution it has not attracted much attention regarding environmental studies although gas emissions especially H_2S have caused complaints.

Much more attention has been given to the environmental effects of the utilization of high temperature geothermal areas in Iceland (Fig. 2). The high temperature areas of Iceland have been reported as 25 to 40 in countdepending on definitions and possible divisions into sub-areas. Ármannsson (2016) considers them 33 (Figure 1) and Ármannsson et al. (2009) consider 19 of them as producible.

The possible utilization has been constrained by a Master Plan for possible energy sources in which all possibilities have been considered with respect to economic viability and environmental effects, grouping hydropower and geothermal options into three groups, i.e. energy utilization option,on hold option and protection option (Hreinsson 2012). The 19 areas considered proucible and subareas that are considered in the Master plan are listed and briefly described in Table 1.

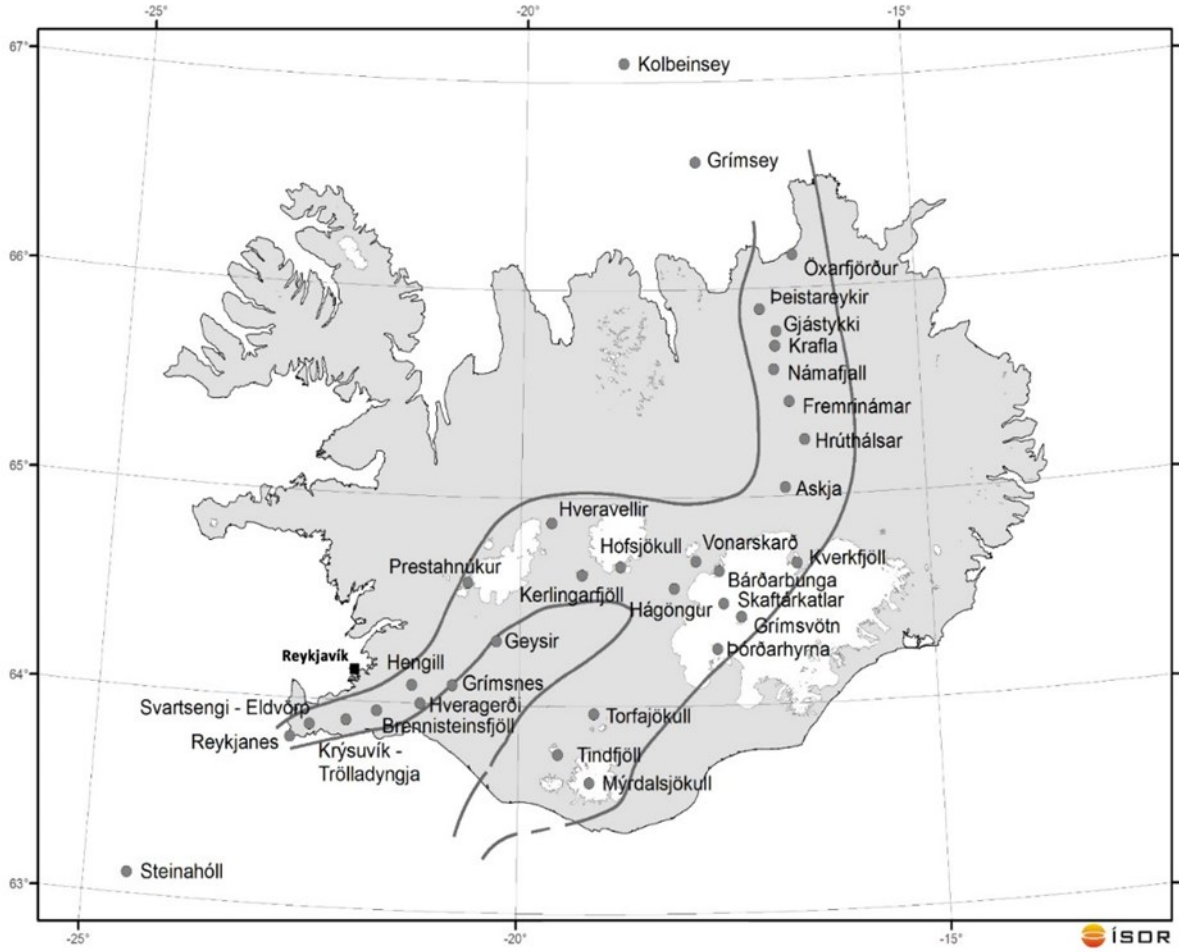

Figure 2: High temperature geothermal areas in Iceland.

Table 1. Producible high temperature geothermal areas in Iceland.

Name	Size km^2	Subareas	T°C	Method of temperature estimation	Status	Master plan category (https://www.althingi.is/altext/141/s/0892.html)
Reykjanes	3-5		325 (540)*	Logging	100 MW$_e$ power plant. More planned. IDDP well	Energy utilization
Svartsengi-Eldvörp	11	Svartsengi Eldvörp	240 270	Logging	60 MW$_e$ power plant. 190 MW$_t$ space heating plant	Energy utilization
Krýsuvík	60	Krýsuvík, Sveifluháls Trölladyngja Sandfell Austurengjar	230 355	Logging	Exploration 15-20 wells drilled	Energy utilization
				Logging	3 wells drilled	On hold
					Surface exploration	Energy utilization On hold
Brenni-steinsfjöll	2		240	Equilibrium with alteration minerals, postulated	Reconnaissance	Protection
Hengill	100	Nesjavellir Hellisheidi Hverahlíd Ölkelduháls Innstidalur Þverárdalur Meitillinn	380 310 320 210 310 280	Logging Logging Logging Logging Logging Logging	120 MW$_e$ power plant. 300 MW$_t$ space heating plant 300 MWe power plant. Increase to 400 MWt planned 133MW$_t$ space heating plant Exploration. 3 wells drilled EIA ready. Exploration 1well drilled Exploration Exploration	Energy utilization Energy utilization Energy utilization Not recorded On hold On hold Energy utilization

		Gráuhnúkar Bitra Grændalur Ölfusdalur	300 275 250-270 240	Logging Logging Geothermometry Logging	Exploration Exploration Exploration Exploration 6 wells drilled. EIA ready	Energy utilization Protection Protection On hold On hold
Geysir	3		240	Geothermometry	Reconnaissance.	Protection
Hveravellir	2.5		280	Geothermometry	Surface exploration	Not recorded
Kerlingar-fjöll	7		300	Geothermometry	Surface exploration	Protection
Torfajökull	140	Reykjadalir Jökulgil	340	Geothermometry	Surface exploration	Not recorded
Hágöngur	8		310	Logging	1 well drilled 2360 m. Fluid temperature 260°C. Max. Temperature 312°C	On hold
Vonarskard	11		310	Geothermometry	Reconnaissance	Not recorded
Kverkfjöll	31		300	Geothermometry	Surface exploration	Not recorded
Askja	25		275	Geothermometry	Research on Lake Öskjuvatn. Volcanology. Fumaroles	Not recorded
Hrúthálsar	7				Reconnaissance	On hold
Fremri námar	4		270	Geothermometry	Preliminary surface exploration	On hold
Námafjall Bjarnarflag	20		335	Logging	3 MW_e power plant. Diatomite factory 1969-2004. 90 MW_e power plant planned	Energy utilization
Krafla	30		350 (500)*	Logging	60 MW_e power plant. Increase planned. IDDP well	Energy utilization

Gjástykki	11		280	Geothermometry	Surface exploration. 600 m deep well	Protection
Theista-reykir	20		380	Logging	90 MW_e power plant	Energy utilization

*Horner plot analysis of heatup data for IDDP wells

2 LANDSCAPE/SCENERY CHANGES

2.1 Exploration stage

The geothermal exploration stage consists of surface geoscientific studies and culminates in the drilling of deep exploration wells and subsequent well testing if results of drilling are positive (i.e. sufficient temperature and permeability are found). The geoscientific studies generally involve teams of scientists and technicians that need to access the study area to conduct measurements or collect samples of geothermal fluids (steam and water) or rocks. These studies involve negligible environmental impacts. The exploration drilling, on the other hand, creates some impacts such as access roads and platforms and associated water holding ponds that need to be constructed, large drilling rigs which are installed, and subsequent discharge testing that brings geothermal fluids to the surface. The installation of access roads and drill pads involves landscape and scenery changes. The magnitude of these effects depends on the location. If the drill site is located in a hilly area and these effects are greater than they would be on flat ground. During drilling the presence of the drill rig can have a temporary effect on the landscape. If possible high points are avoided for the location of drill rigs. Bright lights that are needed around the drilling operation also enhance the visual impact after dark. This is a relatively small effect and temporary in nature. Similarly, during well testing a visible steam plume will rise from the well site. This effect is also relatively minor and reversible. The landscape effects of access roads and well pads can be reduced by the use of directional drilling technology, which allows the developer to drill a number of wells from the same drill pad.

2.2 Construction stage

During the construction stage significant scenery/landscape effects cannot be avoided. Construction of surface installations such as power plants, cooling towers, separator stations, pipelines, and transmission lines will certainly involve permanent changes to the landscape in the area developed. These effects can be minimized but not avoided altogether. The extent of these effects depends on the landscape and local vegetation. The siting of the constructions is not based on changes to landscape and scenery only but changes to vegetation, effects of noise, distance from drilling area and main power lines may have a bearing. In hilly,varied areas several locations may be possible and for EIA the possible locations will be photographed from critical points and the constructions and possible steam flow after start of production photoshopped in This has been the case with the EIAs for the plants proposed at Bjarnarflag (Hönnun hf. 2003) and Hverahlíð (VSÓ Ráðgjöf 2008)) where in each case 3 posssible locations have been suggested but one chosen as most desirable. For Bjarnarflag (Fig.3) a table was constructed listing several consequences of each location and each given a mark from 1 to 3 where 1 was the best choice, 2 was intermediate and 3 thecworst choice (Table 2) (Hönnun hf. 2003). In Hverahlíð the least visible site was not recommended as it was an unspoilt popular tourist site (VSÓ Ráðgjöf 2008). In an open area such as Theistareykir the location is not critical as regards visibility and closeness to the drilling area minimizing the extent of pipelines is probsbly the most important consideration and thus only one site was considered in the EIA (Mannvit 2010) and in Reykjanes due to the smallness of the area there is only one possible construction area (VSÓ 2001).

Table 2. Bjarnarflag. Comparison of possible construction sites (1 represents best choice, 2 is intermediate and 3 is the worst choice)

Parameter	Site A	Site B	Site C
Geology – Natural risk	1	3	2
Disturbance due to soil movement	2	1	3
Vegetation	1	3	2
Size of operation area	1	2	3
Cost	1	2	3
Scenery	1	2	3
Noise	1	2	3

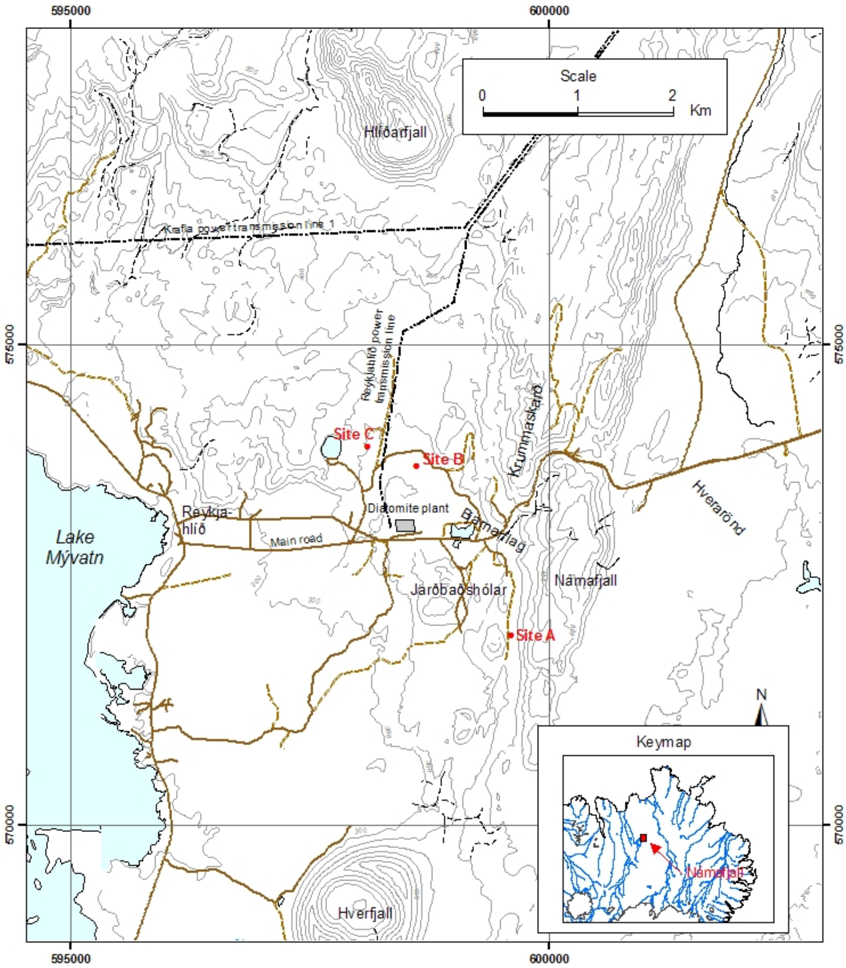

Figure 3: Bjarnarflag, a map showing the three proposed sites, the present 11 kV power transmission line and the Krafla I power transmission line

2.3 Operation stage

The landscape effects of the operation stage *per se* are the thin steam plume rising from the cooling tower and steam plumes that rise from wells that are taken off-line temporarily during maintenance. But the presence of the larger structures is permanent in the landscape from the construction stage.

The land use footprint of different energy options, measured in units of km^2/TW-hr/yr, is a useful parameter for comparing their respective environmental impact. However, this parameter is blind to the environmental properties of the areas as it does not take issues such as scenic beauty, biodiversity, or overall protection value into account. Some energy options are more or less independent of location and can thus be placed in areas of limited environmental value whereas others such as geothermal and hydro are more site specific. And as volcanic geothermal resources, in Iceland and elsewhere, are commonly located in areas of significant natural beauty the scenic impact of geothermal power projects may be relatively more important than for other energy projects that can be located in less valuable areas. It is, nevertheless, of interest for this discussion to compare the land use footprint of geothermal energy to other energy options.

The land use footprint of geothermal power plants is smaller than for comparable installations using other renewable energy sources such as hydro, solar, and wind (McDonald et al., 2009; MIT 2006). In 3the land use intensity or the area of land needed to produce a unit amount of energy in units of km^2/TW-hr/yr (McDonald et al. 2009) for different energy sources is compared. Fig. 4 shows that of the energy sources considered only nuclear power has a smaller land use footprint than geothermal energy. It is also worth noting that the nature of the land use requirements for different energy sources is very different. The land used for hydropower production, solar plants, or coal mining is completely unusable for other purposes, whereas only about 5% of the total area used for geothermal power production is used for civil installations (well pads, access roads, pipelines, separator stations, power plants, cooling towers, switchyards, etc.) (McDonald et al. 2009; MIT 2006) leaving the remaining 95% of the land for other purposes such as agriculture, reforestation, or preservation of natural conditions.

Land use intensity is not necessarily the same as visual impact. Again, geothermal energy compares favorably to other energy sources when the visual impacts are considered. The cooling towers of geothermal power plants are relatively low compared to those of coal fired and nuclear power plants and the wind turbines of wind farms (MIT 2006).

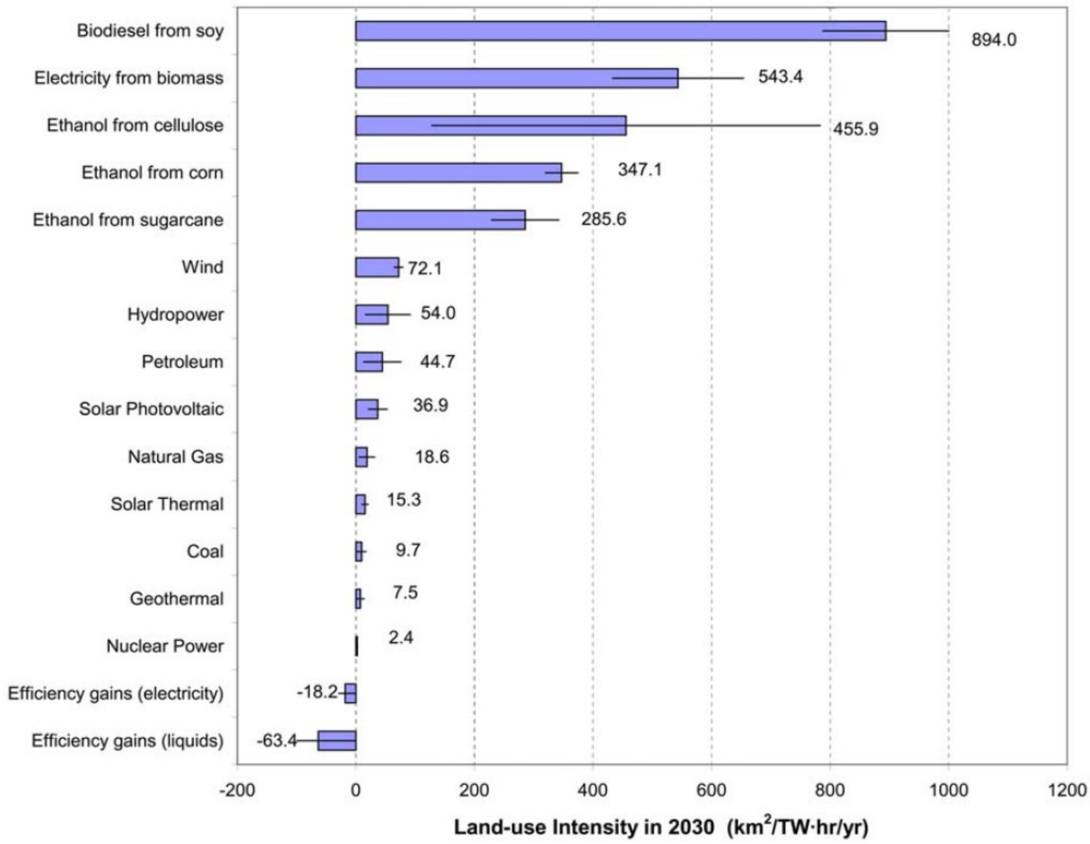

Figure 4. Land use intensity of different energy production (and conservation) sources. Note that only nuclear power has a smaller land use foot print. From MacDonald et al. (2009)

3 EFFECTS ON VEGETATION

3.1 Exploration stage

The unavoidable effects on vegetation during the exploration drilling stage are limited to the removal of vegetation required for the installation of access roads and well pads. Necessary measures must of course be taken to avoid soil erosion resulting from the civil works Vegetation damage has been reported where wells have discharged steam and liquid directly into the air during discharge tests (Tuyor et al., 2005). This practice is no longer common in the industry and most often discharge tests are carried out with a separator that separates the steam and the liquid and a silencer. The current practice (i.e. use of separators) has not been reported to damage vegetation around well sites although H_2S in the steam may have affected vegetation (see section on gas emissions below). Similarly, if the separated water is released on the surface it can cause thermal damage to local vegetation. This is not general practice because the separated water is either reinjected or accumulated in ponds and removed or treated.

3.2 Construction stage

The unavoidable adverse effects experienced during the construction stage are of the same nature as those during the exploration stage, i.e. removal of vegetation to make way for the surface installations such as power plants, cooling towers, separator stations, pipelines, and transmission lines, but on a larger scale. These effects should be minimized by selection of sites for the installations where the vegetation is less sensitive and of less conservation value.

3.3 Operation stage

Adverse effects on vegetation during the operation stage are limited. H_2S emitted from the cooling towers of geothermal power plants may be oxidized resulting in acid rain. If wells are allowed to discharge directly into the atmosphere while off line during maintenance breaks the hot water may cause damage to the surrounding vegetation. Finally, vegetation may be affected during the production stage as a result of changes in the extent of surface manifestations Surface manifestations are known to change in response to geothermal power production. The flow rate from hot springs (where deep geothermal liquid is discharged) generally decreases as a result of production (Hunt, 2001) but the steam venting activity (involving steaming grounds, mud pits and steam heated surface waters) is known to increase (Hunt, 2001; Fridriksson et al., 2010). If the extent of surface activity changes, the previous balance between thermophilic and thermophobic plants may be altered locally.

Changes in surface activity due to geothermal utilization might affect the habitats of thermophilic species. However, as noted above geothermal utilization affects different surface manifestations in different ways. While the activity of the most common surface manifestations, fumarole fields and mud pits, generally increases, the flow from hot springs may decrease or cease altogether.

The flora of Iceland consists of 438 species the majority of which are found in high temperature geothermal areas, mosses being a very significant part (Kristinsson 1986). *Ophioglossum azoricum* and *Plantago major* which are plants that grow almost exclusively in geothermal areas, are quite widespread in geothermal areas. *Thelypteris phegopteris* is common around hot pools but quite rare in North Iceland. For this type of vegetation very little disturbance is expected except during drill-site preparation and road construction, which may cause a slight reduction in vegetation cover. The well pads can be vegetated with grass after drilling and welltesting. Trees can be planted on the pads and the surrounding areas. With the large amount of rainfall in most areas, afforestation should be quite easy.

Conditions for very rich ecosystems of hot spring microorganisms are very common in Icelanic geothermal areas and unuaual species have to be searched for and carefully monitored.

4 EFFECTS ON FAUNA

4.1 Exploration stage

The construction of access roads and well pads may, if not properly planned reduce the habitats for the larger fauna. Also, if the installation of access roads causes soil erosion this may have adverse effects on fish and other animals in rivers receiving the eroded soil (Hunt, 2001). For this, as well as for other reasons, it is of critical importance to take soil erosion into account when designing access roads to geothermal wells. Also, if the installation of access roads causes soil erosion this may have adverse effects on fish and other animals in rivers receiving the eroded soil (Hunt, 2001). For this, as well as for other reasons, it is of critical importance to take soil erosion into account when designing access roads to geothermal wells. Directional drilling technology minimizes the land requirements and thus the habitat loss due to human activities.

4.2 Construction stage

Adverse effects on fauna can be reduced by planning that minimizes the intrusion to sensitive habitats.

4.3 Operation stage

Adverse effects on fauna resulting from the operation of the power plant *per se* are limited but, of course, the effects from the construction stage remain.The only wild mammals that are known in these areas are minks, foxes, mice and rats and in East Iceland reindeer.Sheep from farms are very common. None of these are likely to be affected. Birds on the other hand are quitte common, for instance at least 43 species are known to nest on the Reykjanes peninsula where several geothermal areas are located. As most of these birds nest in cliffs geothermal utilization is not likely to affect them unless drilling is undertaken close to the cliffs.

5 EFFECTS ON SURFACE WATER AND GROUNDWATER

5.1 Exploration stage

During drilling the main threats to the surface water are potential spilling of drilling circulation fluid to the environment. Sometimes chemical additives are used to change the properties of the drilling fluid and these chemicals are generally not desirable in surface waters. Similarly, there is always a possibility of fuel spills as the drilling is powered by large diesel engines. These problems can be avoided if proper environmental quality standards are followed on the drill site.

There is a risk of contamination of surface and ground waters if separated geothermal brine is allowed to flow on the surface during discharge tests. There is alsoalways a possibility that the geothermal brine may enter the surface environment, i.e. if ponds fail or if they overflow due to heavy rains. This is highly undesirable but it must be pointed out that separated geothermal brine is not an acutely toxic liquid and a limited spill, resulting from an overflow due to rain, would not cause irreversible damage to the surface water or the aquatic wildlife.

5.2 Construction stage

The risk is not considered greater than that than from other construction activities.

5.3 Operation stage

The main risk involves intentional or accidental release of separated geothermal brine to the environment where it will end up in surface and/or ground water and there is always a possibility that ponds may fail or overflow. Geothermal developers must strive to reduce such risks by ensuring that the civil works are of sufficient quality and by ensuring that surface runoff cannot enter the pool and result in overflow during heavy rains.

Geothermal production generally results in lowered pressure at the reservoir level. In some cases such pressure drops have resulted in the lowering of water level in ground water reservoirs (Hunt, 2001). This would reduce the flow of cold groundwater from springs and call for deeper fresh water wells.

6 EFFECTS ON LOCAL CLIMATE

6.1 Exploration stage

During drilling effects on local climate are not likely to be felt but during discharge tests steam may create a tendency for fog formation and icing on roads in a cold climate

6.2 Construction stage

This stage is not likely to affect the local climate.

6.3 Operation stage

Some steam release will take place from silencers especially if reinjection is not practiced and the low efficiency of geothermal power stations causes them to emit a relatively large amount of water vapor from cooling towers per unit capacity. Thus the considerable outflow of water vapour from the silencers, condensate trap valves, hot-water drains and the cooling towers, may create a tendency for local fog formation and icing of roads in winter in colder climates. The problem is greater for stations with mechanical draught cooling towers than for natural draught cooling towers which have a greater plume rise (Ellis 1978).

In Iceland the natural climate is mostly wet and windy and thus effects like fog formation or additional icing of roads are not likely to be of major concern.

7 EFFECTS ON TOURISM

7.1 Exploration stage

Geothermal power stations are in many instances situated in areas of outstanding natural beauty so tourists are expected to be attracted. Tourists, however, are not likely to come just to see a geothermal power plant. During the exploration stage drilling operations might involve improved roads and possibly increased service facilities which could increase the number of tourists visiting.

7.2 Construction stage

The power plant as such is not considered to be a tourist attraction and might in fact repel some tourists if utmost care is not taken at this stage. It is important that the buildings and other surface installations blend well with the surroundings and that the more unattractive parts such as switchyards are situated discreetly. During this stage improved roads and increased service facilities are likely to draw an increased number of tourists to the area as has been the case elsewhere. Experience shows that good facilities such as visitors' centers with interesting displays on geothermal energy and each power plant have enjoyed great popularity with tourists (e.g. Axtmann 1974). The building of such facilities would be a part of the constructions erected during this stage.

7.3 Operation stage

At this stage the visitors' center would be operating. Peripheral activities such as spa facilities have been shown to be popular and draw tourists. In Iceland the Blue Lagoon at the Svartsengi power plant is the most visited tourist facility in the country attracting more than 1.000,000 visitors every year. This is particularly impressive considering that the total number of foreign tourists in the country is of the order of 2.000,000 (https://www.gamma.is/media/skjol/Gamma-Tourism.pdf). Although the proximity of the Blue Lagoon to the international airport plays a significant role these numbers, nevertheless, illustrate that geothermal development is not only compatible with tourism but may present an opportunity for instalment of significant tourist attractions.

8 EFFECTS ON SEISMIC ACTIVITY

8.1 Exploration stage

High temperature geothermal reservoirs are most often located in tectonically active areas where earthquakes are likely to take place for natural reasons (Hunt, 2001). When geothermal wells are drilled circulation fluid is pumped through the drill string to cool the equipment and bring drill cuttings to the surface. The pressure of the circulation fluid may trigger movements on faults that were already near the breaking point. Such earthquakes are generally very small and only detectable if local seismic networks are set up in the area of the drilling. These earthquakes can provide valuable information for the geothermal developer as they reveal the location and orientation of active faults that are feasible drilling targets.

In Basel, Switzerland during a hot dry rock enhanced geothermal systems project geothermal stimulation, seismic events reached the trip point of Richter Magnitude M_L 2.9 six days after the main stimulation was started on December 2 2006. Further tremors exceeding magnitude 3 were recorded on 6 January (measuring 3.1), 16 January 2007 (3.2), and 2 February 2007 (3.2).

In all, between December 2006 and March 2007, the six borehole seismometers installed near the Basel injection well recorded more than 13,500 potential events connected with the geothermal project which was eventually abandoned (Schanz et al. 2007)

8.2 Construction stage

There is no more risk of earthquakes during the construction stage of geothermal power plants than from other construction work.

8.3 Operation stage

Experience has shown that the utilization of some geothermal fields has resulted in induced seismicity (Hunt, 2001). These earthquakes seem to result from the liquid reinjection as the frequency of earthquakes decreases when reinjection has stopped and increases when it has started again (Hunt, 2001). Accumulation of earthquake data which provides information on the infrastructure of the geothermal areas and how production affects them especially with regard to stimulated earthquakes, is carried out continuously.

An example from Iceland is from the Hengill-Hellisheiði area which is seismically active, The largest individual earthquakes have reached magnitudes of 5.5 Ml. The injection site for the geothermal fluid from a power plant at Húsmúli was taken into use in September 2011 with a full scale injection of 550 L/s. An intense seismic swarm followed with 4 earthquakes reaching magnitudes over 3 Ml (the largest was Ml = 3.8) (Ágústsson et al. 2015).

9 NOISE

9.1 Exploration stage

Surface exploration causes minimum noise. On the other hand once drilling starts considerable noise may be experienced. In Table 3 noise created by different activities resulting from geothermal utilization is listed, and in Table 4 noise limits according to Icelandic regulations.

Table 3. Noise created by geothermal utilization (Brown1995)

Stage	Operation	Noise level dB(A)
Drilling	Air drilling	120
	Air drilling with suitable muffling	80
	Mud drilling	80
	Mud drilling with maximum muffling	55
Discharge	Vertical	125
	Through drum silencer	70-110
	Through new design rock muffler	65
Construction	Use of heavy machinery	90
	Use of heavy machinery muffling exhaust	Reduced
Production	Pipeline and vent discharge noise	Usually acceptable
	Cooling tower fans	To be monitored
	Steam ejectors	To be monitored
	Turbine hum	To be monitored

Table 4. Limits on average noise level in a work place /Disregarding hearing protection) (Vinnueftirlit ríkisins, Administration of Occupational Safety and Health, Iceland)

Noise level dB(A)	Duration/day	Noise exposure (Pa^2h)
85	8 hours	1
91	2 hours	1
97	30 mins	1
102	8 mins	1
115	30 secs	1
140	Peak value	

Thus drilling may cause noise that exceeds all limits if suitable measures are not taken for its reduction. The most common measures are keeping the drill rig engines inside sound enclosures, covering spaces within the rig with rubber mats and covering the mast with a sound muffling cap.

The discharge from an unmuffled well, especially a dry steam well, can be extremely unpleasant and exceed all limits. For dry steam wells rock mufflers have traditionally been most effective but for two phase discharge drum cylinders that act as liquid/vapor separators at atmospheric pressure have been most commonly used. In some instances geothermal areas situated in populated areas have been utilized, and for these special new rock mufflers combining the design of the traditional drum silencers and rock mufflers have been used to bring the noise down to acceptable levels.

Noise level is reduced with distance from the noise source at a rate of approximately 6 dB(A) as the distance from the source is doubled (Hunt, 2001). This is assuming a direct and homogeneous sound field.

9.2 Construction stage

As in any civil engineering project the use of heavy machinery is required during construction and the noise created subject to the same limitations. The noise from the operation of heavy machinery can be expected to be 90 dB(A). In a direct sound field the noise level from such an operation will be at 50 dB(A) at 100 m distance from the source.

9.3 Operation stage

Normally a geothermal plant is so designed that a limit of 65-70 dB is observed. As stated above some geothermal areas situated in populated areas have been utilized in recent years and additional measures have been taken to reduce the noise even further. Such measures include keeping control valves inside separate enclosures and the use of specifically designed ball valves that replace butterfly valves. The propagation of noise in the neighbourhood of geothermal plants can be modeled and the results used to modify environmental conditions (soft ground at well sites, use of acoustic barriers etc.) to attenuate the noise impact.

10 GAS EMISSIONS/ODOUR

10.1 Exploration stage

Preparation for drilling involves a lot of truck traffic with attendant petrol and diesel fumes and once drilling starts the drill rig engines will create additional diesel fumes. Gas, mainly carbon dioxide, may accumulate during the drilling and heating of a well and possibly be released.

Upon discharge samples will be drawn and the amount of release quantified. More detailed measurements of distribution and modeling taking into account geographical and climatic conditions should be carried out. The major offending gases are usually carbon dioxide and hydrogen sulfide. Minor gases of environmental concern are ammonia, methane, mercury, and boron. Carbon dioxide and methane are so-called greenhouse gases because they contribute to the greenhouse effect whereas the other gases are toxic, boron especially to plants (Ármannsson and Kristmannsdóttir 1992). Carbon dioxide and hydrogen sulfide are heavier than air and may accumulate in lows where they can cause asphyxiation.

10.2 Construction stage

Trucks and heavy machinery burning diesel will be brought in with attendant fumes.

10.3 Operation stage

Most conventional geothermal power plants (flash) and even some binary plants will release the geothermal gas to the atmosphere. The gas content of geothermal steam varies between fields but is commonly less than 1% of the mass. Most of this gas is generally CO_2 (commonly ~90%) and the second most significant is H_2S. Other gases include N_2, H_2, Ar, CH_4, and sometimes NH_3 (Hunt, 2001). Trace quantities of B and Hg may also be present in the geothermal steam. However, compared to most other energy sources the gas release from geothermal energy generation is benign.

Kagel et al. (2007) compare the gas release from geothermal power production to those of fossil fuels. Their data show that the CO_2 release from a conventional flash geothermal plant is about 27 kg/MWh as compared to 550 to 1000 kg/MWh for fossil fuel plants (gas and coal respectively). The higher end of CO_2 emission per unit energy (100 kg/MWh) is relatively high for geothermal power but still only 1/5 to 1/10 of the emissions from fossil fuel.

Similarly, the sulfur release from geothermal power plants is only 1/30 of the release from coal and oil fired power plants (Kagel et al., 2007), but power plants using natural gas release somewhat less. Furthermore, no NOx compounds are released from geothermal power production but the release of these compounds is an environmental concern for all fossil fuel power plants (Kagel et al., 2007).

Carbon dioxide from geothermal power plants is usually released to the atmosphere but experiments in Hellisheidi, Iceland suggest that it may be possible to inject it into basalt layers where it will be fixed as calcium carbonate (Gíslason et al., 2010; Matter et al. 2011). Hydrogen sulfide is toxic in high concentrations but its main nuisance effects lie in its unpleasant odor and suspicion that it may have a deleterious effect on plants. Therefore quite stringent regulations apply in in some areas, especially agricultural areas. In Table 5 the effects of hydrogen sulfide at various concentrations in air are listed.

Table 5. Effect of hydrogen sulphide on human beings (Aguilar 2004)

Concentration mg/kg	Effect
0.0005-0.03	Odor threshold
0.3	Distinct odor. May cause headaches
2-5	Odor intensive and offensive
10-20	Eye, lung irritation. Limit for 8 hour work in most countries
100	Can cause loss of smell
650-700	May cause sudden death
750	Rapid death likely

If hydrogen sulfide is released into the atmosphere its fate is dependent on the climate. It is very quickly washed out of air in wet weather and although it is unstable thermodynamically and might be expected to be converted to sulfur dioxide this seems to be a relatively slow process unless a photochemical reaction is activated in sunlight. Thus the conversion to sulphur dioxide and precipitation as acid rain is unlikely in the Icelandic climate.

Many geothermal producers are required to prevent the release of hydrogen sulfide into the atmosphere and remove it from the steam. The most common methods such as the Claus-Selectox involve oxidation to sulfur with the aid of suitable catalysts. The product is either buried, which involves extensive trucking and excavation work, or marketed which can only be economic if it can be utilized close to the source. Experiments employing bacterial oxidation have shown promise. Reinjection of hydrogen sulfide is also possible (Gunnarsson et al., 2011) but needs hydrological and chemical studies and long term effects on the geothermal reservoir are not known.

The CarbFix2 project aims to capture and store the CO_2 and H_2S emissions from the Hellisheiði geothermal power plant in Iceland by underground mineral storage. The gas mixture is captured directly by its dissolution into water at elevated pressure (Gíslason et al. 2010, Gunnarsson et al. 2011). This fluid is then injected, along with effluent geothermal water, into subsurface basalts to mineralize the dissolved acid gases as carbonates and sulfides.

11 SOCIO-ECONOMIC IMPACTS

11.1 Exploration stage

The socioeconomic effects of geothermal development are limited during the exploration stage. However, installation of access roads may improve local infrastructure in some cases. Similarly, local people may enjoy temporary employment opportunities during the drilling stage and as field assistants for the geoscientific surveys. These effects are not permanent and of a relatively low impact

1.2 Construction stage

During the construction stage more employment opportunities for local people arise. A large number of construction workers as well as workers for related services need to be employed at this stage. At this stage, roads are generally also significantly improved. When the power plant at Krafla, North Iceland was constructed both the Krafla and the neighbouring Námafjall areas had been explored but Krafla was chosen for production as it was remote and considered less likely to cause disturbances. But as soon as the road to Krafla had been built a stream of tourists used that road to reach attractions in the neighbourhood and suggestions that the plant should be abandoned as it was an eyesore and disturbed the view of the tourists have been heard.

11.3 Operation stage

The most significant socioeconomic effects of geothermal development on local communities are experienced during the operation stage. These effects vary significantly from one place to another depending on the population density in the area and other factors. The area has been generally opened up and tourism may play a significant part in the local economy such as in Krafla.

12 RISKS

12.1 Landslides

Landslides are liable to take place 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 upper basement in geothermal fields are often thermally altered and can become increasingly so during utilization, the landslide factor has to be carefully monitored.

For schemes in areas of high relief and steep terrain, landslides are a potential hazard.Landslides may be triggered either:

a) Naturally, by heavy rain or earthquake; or
b) As a result of construction work, which may have removed the “toe” of the slide.

In certain kinds of terrain, possible landslides place severe constraints on the placement of both wells and power plants or other facilities. Well blowouts may occur due to casing failure as a result of landslide movement.

Locating well pads on islands of stable bedrock and drilling one or more slant holes from a single site makes it possible to maintain the bottom hole spacing in the producing horizons needed to adequately develop the resource while locating well heads on stable ground. The costs of necessary onsite geologicand soil stability studies, though high, are small compared to the loss of a well as the result of a blowout. Similar but more stringent considerations control the siting of power plants. The costs of slope failure either upslope from or beneath a power plant would involve much more serious losses. Limitations on the distance steam can be carried by a pipeline place severe constraints on the selection of available sites (Crittenden, 1981). Such events are relatively rare but the result may be severe, such as for the landslide on 5 January 1991 in Zunil field (Guatemala), when 23 people were killed (Goff and Goff, 1997).

12.2 Steam pillow explosions

Lowering of the groundwater table by fluid withdrawal can lead to the formation or accelerated growth of steam pillows and subsequent boiling and degassing of a field. Such developments may induce major explosions that in the past have killed a number of people (Hunt 2001, Goff and Goff 1997).

Although relatively rare, hydrothermal eruptions do occur and hence need to be assessed. Eruptions occur when steam pressure in the near surface aquifers exceeds the overlying lithostatic pressure and the overburden is then ejected to form a crater, which varies in diameter (15-500 m) and in depth (generally less than 10 m). This happened in The Ahuachapan field in El Salvador in 1990

(Goff and Goff, 1997) and in the Wairakei field in New Zealand (Hunt, 2001). Eruptions have occurred in Krafla, and Krýsuvík in Iceland. In assessing the likelihood of a hydrothermal eruption hazard evidence of previous hydrothermal eruptions, increasing steam flow to the surface from reservoir pressure drawdown or an expanding steam zone are some of the factors to be considered. Other points to be considered are, shallow gas pockets, and kicks or blowouts during drilling. Drilling can also cause eruptions if the casing string is set too shallow, or if the casing develops a leak. Reinjection under pressure of fluids at temperatures >100/C also needs care as there is a possibility that such water will rise rapidly to the surface and heat the local groundwater, resulting in an eruption.

12.3 Fracture movements

In connection with magmatic or major seismic events fractures may be expected to move or open up causing changes in flow, and general risk in a geothermal area. In,Námafjall North Iceland the geothermal system was cooled down considerably when fractures opened up and fluid from a large cool aquifer entered the geothermal system.

12.4 Earthquakes

As geothermal areas are usually located in active zones they are prone to earthquake activity which needs to be monitored. The Icelandic Meteorological Office runs a countrywide seismometer network as a warning system for natural risks. Natural seismicity may be changed by fluid withdrawal, and reinjection may induce microseismicity, and in some geothermal areas Iceland Geosurvey runs an additional network to gather information on the infrastructure of the geothermal areas and how production affects them., especially with regard to stimulated earthquakes.

12.5 Volcanic eruptions

Being located in magmatically active zones many geothermal areas are at a considerable risk regarding magmatic events. The Krafla eruption is a good example affecting both the Krafla and the Námafjall areas. In Krafla wells were destroyed, by movements and contamination by magmatic gases causing deposits clogging up wells, and magma was found to enter wells (Ármannsson et al. 1982). In Bjarnarflag a volcanic eruption through a borehole was observed (Larsen et al. 1978).

12.6 Gas collected in lows

As the major geothermal gases, carbon dioxide and hydrogen sulphide are heavier than air they will accumulate in natural lows in still weather. Borehole cellars are also very rsky places to visit if here are significant gas emissions from a borehole. Carbon dioxide can cause choking and hydrogen sulphide is toxic.

13. CONCLUSIONS

In Iceland the possible environmental effects and risks have been considered in EIAs and action taken. During the operation of geothermal power plants few problems have arisen and monitoring appears to be effective.

Improvements in technology such as directional drilling have reduced land use and in muffling noise from drilling and power plants. The reijection of hydrogen sulphide and carbon dioxide into basalt are also hopeful signs of decreased gas emissions.

Iceland‘s Energy Resources Master Plan in which about 100 energy projects have been assessed based on various aspects of economic and technical feasibility, and environmental and social impacts has put beneficial constraints on energy production in Iceland.

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