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# ENVIRONMENTAL MANAGEMENT AND MONITORING IN ICELAND: REINJECTION AND GAS SEQUESTRATION AT THE HELLISHEIDI POWER PLANT

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## ABSTRACT

In the Hengill geothermal system monitoring programmes have been developed in connection with Environmental Impact Assessment. The aim is to measure the response of the Nesjavellir and Hellisheidi power plants through extraction of geothermal fluid as well as to record the influence of the utilization on the environment. The data collected is used to calibrate numerical prediction models of the geothermal field and is also the key to solve most problems which may come up in the operation. The CarbFix and SulFix projects have proved to be successful methods to reduce emission of $CO_2$ and $H_2S$ emission from power plants to the atmosphere.

## 1. INTRODUCTION

The Hengill geothermal area lies in the middle of the western volcanic zone in Iceland, on the plate boundary between North America and the European crustal plates; this boundary runs from Reykjanes in a northeasterly direction towards Langjökull. The plates are diverging at a relative rate of 2 cm/year. This rift zone is also highly permeable and numerous fumaroles and hot springs emerge at the surface. Hengill area is one of the most extensive geothermal areas in the country (Figure 1).

Several potential geothermal fields can be distinguished within the Hengill complex. Only three of these areas have been developed, one for space heating, industrial use and greenhouse heating in the town of Hveragerdi, and at Nesjavellir and Hellisheidi where Reykjavik Energy operates geothermal power plants. The installed capacity at Nesjavellir power plant is 120 $MW_e$ and 290 $MW_{th}$. The Hellisheidi power plant is also a co-generating plant with 303 $MW_e$ and 133 $MW_{th}$ installed.

Extensive geological, geophysical and geochemical surveys have been carried out throughout the Hengill area in conjunction with the Nesjavellir and Hellisheidi projects.

Monitoring programmes have been developed in connection with Environmental Impact Assessment (Table 1). The aim is to measure the response of the Nesjavellir and Hellisheidi geothermal systems through extraction of geothermal fluid as well as to record the influence of the utilization on the environment. This monitoring will last through the lifetime of the power plants. Background information were collected prior to drilling and testing of production wells. Ever since drilling commenced downhole measurements and flow testing has been a part of the monitoring programme as well as chemical sampling. Currently the monitoring programme is put forward in a number of written operation procedures, and since 2003 the monitoring programme fulfils the requirements of ISO 9001.

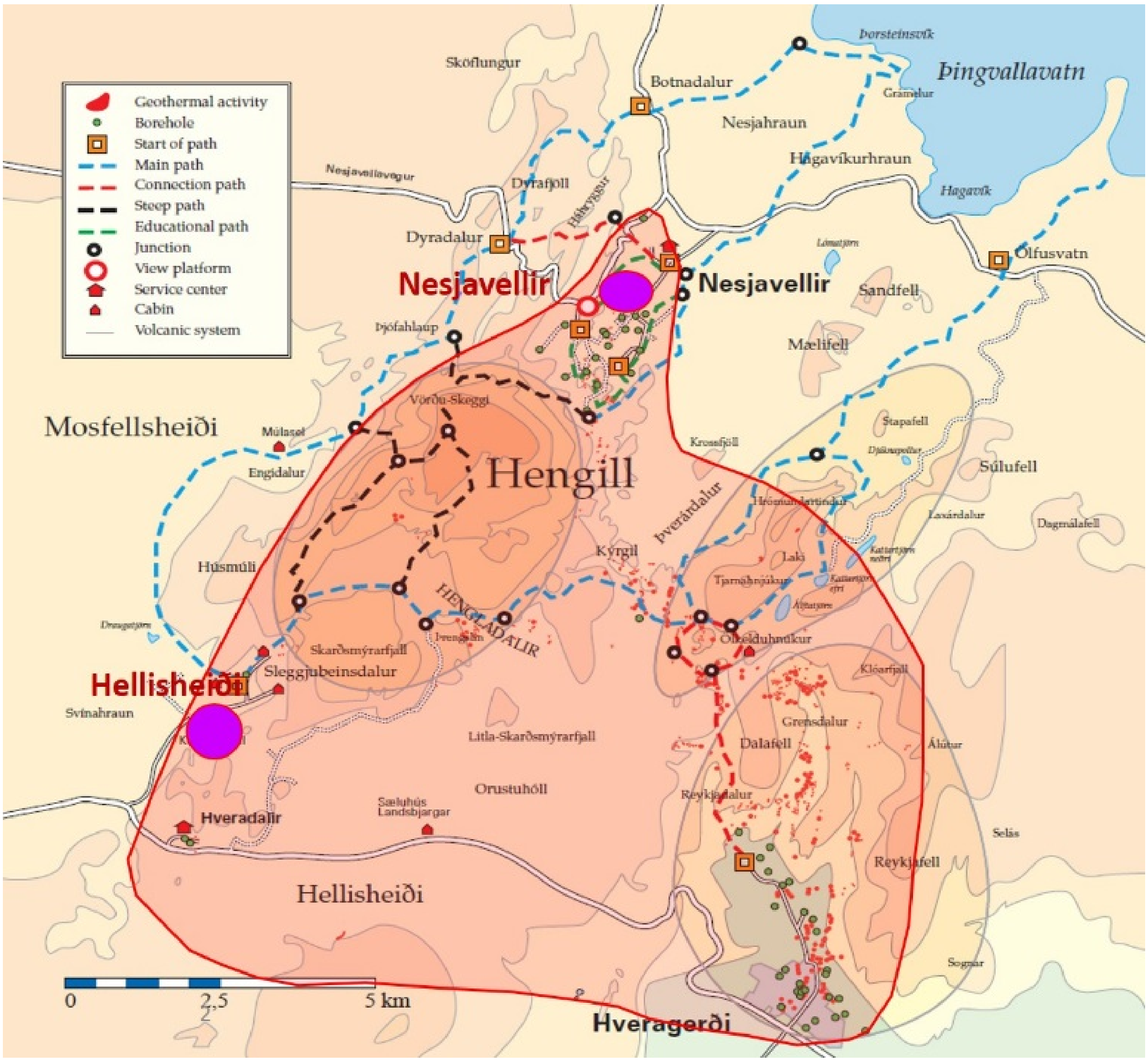


FIGURE 1: Hengill geothermal area showing distribution of resistivity, surface manifestations and power plants

## 2. MONITORING PROGRAMME OF THE GEOTHERMAL RESOURCE

The flow rate from boreholes is measured and the total discharged is calculated for each borehole taking into account the time it has been producing. The measurement of flow rate from discharging wells was limited to test periods when the well discharges into a silencer at well site, using lip pressure and water flow rate from silencer to calculate flow rate and water/steam ratio. With increasing production the boreholes are less and less available for flow measurements, as they are constantly connected to the power plant. Since the year 2000 flow rate is increasingly measured by Tracer Flow Testing or TFT (Hirtz et al., 2001). The advantage of this method is that flow rate can be measured without disturbing the production. From 2004 this method has largely replaced the older method. When boreholes are not in production their water level is monitored or the wellhead pressure is recorded, depending on the characteristics of the each borehole.

TABLE 1: Monitoring programme for Nesjavellir and Hellisheidi power plants and the Hengill area

| **NESJAVELLIR POWER PLANT** | |
|---|---|
| **Monitoring the geothermal field** | **Freq year** |
| Output from drillholes | 1 |
| Chemical composition | 1 |
| Temp. and pressure in boreholes | 1 |
| Revision of reservoir model | 5 |
| **Biological monitoring** | |
| Birds | 5 |
| Vegetation | 10 |
| Trace elements in bio | 5 |
| Biology in Varmagjá | 5 |
| Water temperature | 2-3 |
| **Groundwater monitoring** | |
| Water samples at Thingvallavatn (main) | 0.5 |
| Trace elements in water | 3-5 |
| Revision of groundwater model | |
| **HENGILL AREA** | |
| **Monitoring of land** | |
| Land elevation | 2-4 |
| Gravity measurements | 2-4 |
| Changes of geothermal manifestations | |
| Vegetation around drillholes | 3-5 |

| **HELLISHEIDI POWER PLANT** | |
|---|---|
| **Monitoring the geothermal field** | **Freq year** |
| Output from drillholes | 1 |
| Chemical composition | 1 |
| Temp. and pressure in boreholes | 1 |
| Revision of reservoir model | 5 |
| **Biological monitoring** | |
| Birds | 5-10 |
| Vegetation | 10 |
| **Groundwater monitoring** | |
| Groundwater level in drillholes | |
| Water samples from drillholes (main) | 0.5 |
| Trace elements in water in selected wells | 5 |
| Temperature meas. in selected drillholes | |
| Water collection in wells south of Lambafell | 0.5 |
| Revision of groundwater model | |
| **Monitoring of discharge** | |
| Quant. & chemical components in water | 1 |
| Trace elements in water | 5 |
| Quantity & composition of gases | 1 |
| Concentration of $H_2S$ in atmosphere | 0.2 |

Annual downhole temperature and pressure logs have been carried out in selected wells at Nesjavellir and Hellisheidi  In the beginning, several wells were available for the monitoring, but during the last years most production wells have been connected to the power plants limiting, the monitoring programme. This has been met by logging some selected production boreholes during scheduled maintaining stops.

Initially after a borehole starts discharging, frequent sampling is carried out, but in the long run annual sampling from each production wells is preferred in order to evaluate any changes in the reservoir fluid chemistry and gas content. Sampling from a high enthalpy resource involves the sampling of geothermal water, condensed steam and non-condensable gases.

Data collected through the monitoring programme is key information in development of numerical models. It is used for calibration and the model is then used for prediction on future behaviour of the production wells and on pressure drawdown in reservoir.

## 3. ENVIRONMENTAL MONITORING

One of the main missions of Reykjavík Energy is to work in harmony with nature in all issues. All preparations and designs for new power plant have been planned with this mission in mind. A monitoring program for the power plant includes environmental factors such as groundwater and its chemistry.

### 3.1 Groundwater

Groundwater research is important for all geothermal utilization in high-temperature areas, especially when the heat is going to be used for other than electric energy production. Firstly, geothermal water from high-temperature fields cannot be used directly for heating and large volumes of groundwater are needed; secondly, the groundwater flow has to be well-known for planning disposal or reinjection of the geothermal fluid.

The groundwater system in the Hengill and surrounding area is very complicated. Precipitation in this area is among the highest in Iceland but runoff on the surface is very limited. Most of the runoff has thus to take place underground. Concurrent with geothermal reconnaissance, an extensive study was also carried out on groundwater flow, including the drilling of 25-30 research wells, 60-200 m deep.

The main characteristic of the groundwater system in the investigated area is that it is divided from southwest to northeast by a range of mountains formed by Hengill, and the mountain-range towards the south-west. On the eastern side, water flows from Hellisheidi to the east. Hydrology is a little more complex on the western side, with a characteristic area of 15 $km^2$ west of Hengill where the level of the groundwater table is around 172 m above sea level. From there the ground water flows in three directions: west to Ellidaá catchment area, northeast to Þingvallavatn, and to the south until it reaches the sea at Selvogur.

The monitoring of the groundwater is to collect information used in groundwater modelling as well as to collect samples for chemical analysis of major and trace elements.

### 3.2 Reinjection and seismicity

Reinjection of all effluent water production from the Hellisheidi power plant is required by operation permits. The purpose is to protect the surrounding environment, not contaminating groundwater reserves, and to maintain pressure in the system (Gunnarsson, 2011).

Originally, reinjection wells were drilled to the south of the power plant at Gráuhnúkar. Although this area has proven to be a good reinjection area, drilling in the area found temperatures above 300°C making it a prime target for further energy production. The company therefore invested in a new reinjection area to the north of the power plant, Húsmúli, to take over reinjection from the power plant. The injection boreholes, which are directionally drilled and target large active faults, have resulted in swarms of small earthquakes both during drilling, and especially during fluid reinjection tests (Gunnarsson, 2011). The earthquakes associated with testing the reinjection wells were of small magnitudes and had no adverse effects, and as a result received little attention by the community. In spite of that the Húsmúli area was not known to be a particularly active seismic area and the injection pressure of 28 bar was far below the critical stress state of the rock (Gunnarsson, 2013).

The Husmuli reinjection area became fully operational in early September 2011 when reinjection commenced at a rate of around 550 l/s. This was followed by an immediate onset of induced microseismicity of about 1900 earthquakes during the period 10.09-16.10 (Orkustofnun, 2011). About 40 earthquakes were registering over magnitude ML 2.5 and eight earthquakes registering between ML 3.0-4.0. Most of the earthquakes above ML 2.5 were felt in the nearby town of Hveragerdi and the biggest earthquakes were also felt in the capital city of Reykjavik (Bessason et al., 2012).

Despite the induced seismicity, reinjection into the area continued at full pace. Over the next few months, as the area reached a new stress state under these new conditions of large scale reinjection, seismicity subsided and events that could be felt in nearby communities dropped dramatically.

An independent panel consisted of experts from Icelandic Geosurvey, the Icelandic Metrological Survey (IMO), the University of Iceland, Reykjavik Energy and the town of Hveragerdi was established to evaluate the current reinjection and to provide recommendations for future reinjection operations. A report was published in late 2012 (Bessason et al., 2012) with several recommendations. One was to put in place a formal communication route with nearby communities and authorities in case of increased seismic risk.

Reykjavik Energy and ON-Power the current owner and operator of the Hellisheidi power plant also revised its work procedures regarding reinjection and a new traffic light process was put in place for starting large scale reinjection or when significant changes are made in the reinjection from the power plant (Figure 2). The procedure is modelled after AltaRock Energy's decision tree for triggers and mitigation actions from its Newberry EGS demonstration project (Thorsteinsson and Gunnarsson, 2014).

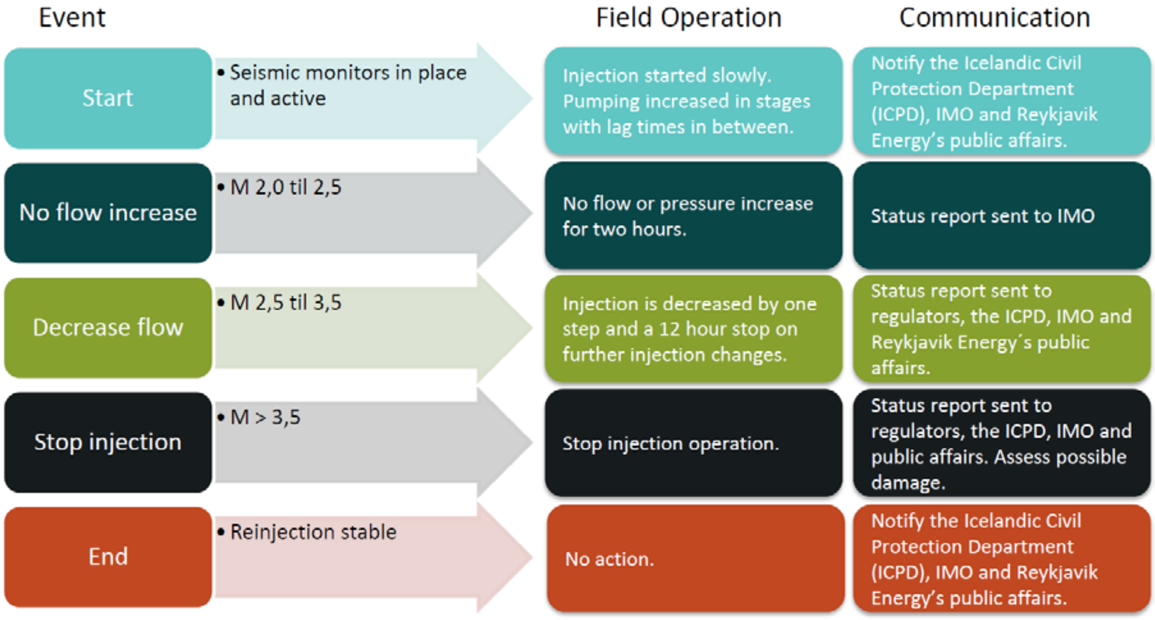


FIGURE 2: Work procedure for large scale reinjection after a temporary shutdown or when significant changes are made in reinjection from the power plant (Thorsteinsson and Gunnarsson, 2014)

### 3.3 Gas emission

Although geothermal power plants produce renewable energy, with very little emissions compared to their fossil fuel counterparts, emissions of the non-condensable gases is an inevitable part the power production. Some of the gases are environmentally important they are greenhouse gases, other are corrosive, toxic, flammable and have bad smell. The origin of the gases is either magmatic, meteoric or they are formed in the geothermal reservoir in water rock reactions. The Hellisheidi power plant annually emits about 40,000 tonnes of $CO_2$ which is about 3% of $CO_2$ emissions from fossil-fuel-burning power plants of a comparable size and about 12,000 tonnes of $H_2S$. Emission of some of these gases, particularly $H_2S$, remains one of the main environmental concerns associated with high-enthalpy geothermal energy utilization in Iceland. A new regulation regarding atmospheric $H_2S$ concentration was issued by the government of Iceland in 2010. The regulation is significantly stricter than the World Health Organization (WHO) Air Quality Guidelines (World Health Organization 2000). This puts high demands on the geothermal industry to reduce atmospheric $H_2S$ concentrations in the vicinity of geothermal power plants.

## 4. CARBFIX AND SULFIX

The CarbFix project initiated at Hellisheidi Geothermal Power Plant in 2007. Its goal is to reduce emissions of carbon dioxide from the power plant by re-injecting it, dissolved in water, into the basaltic bedrock in the power station's vicinity and sequestering it there in mineral form. In 2014 about 250 tons of carbon dioxide had been channelled down into the bedrock at a depth of 400-800 m in the experimental. Samples taken from a monitoring well in the vicinity prove a sequestration rate of 80-90% in mineral form within a year from re-injection. In the autumn 2014 a core sample of rock was taken by drilling in the CarbFix project field. The core clearly showed that carbon-rich precipitates had formed following re-injection of carbon dioxide in the area. The core samples further support the findings of the project that carbon dioxide can be sequestered quickly and permanently in basalt bedrock and thus reduce emissions from this greenhouse gas.

After Hellisheidi Power Plant was commissioned in 2006 geothermal met its most serious challenge for decades. There were more complaints and demands for cleaning the $H_2S$ gas from the atmosphere than had been the case for the Nesjavellir power plant. Plans were up to construct more power plants in the Hengill area and it was declared in Environmental Impact Statement in 2007 that the $H_2S$ emissions from the additional power plants would be scrubbed. There are several methods available to reduce $H_2S$. Among these are chemical methods based on chemical reactions with catalysts involved, biological methods entail the use of microbes to oxidise $H_2S$ and physical methods where $H_2S$ is dissolved in geothermal water an injected well below groundwater aquifers. The last one was selected based on good experience from the CarbFix project and that all the traditional methods have other environmental impact which are difficult to solve. In 2007 a team of Icelandic experts began the development of injecting $H_2S$ into the basaltic bedrock

The CarbFix Project, its methodology and technical equipment have been utilized directly in the SulFix project. The CarbFix project is good example of collaboration between an Icelandic company and universities located on both sides of the Atlantic Ocean. The experience and networks from the CarbFix Project has helped to handle the number of demanding tasks accompanying the SulFix project.

The first step towards that goal, three pilot scale $CO_2$ and $H_2S$ injections were carried out at Hellisheidi geothermal power plant in 2012 within the SulFix and CarbFix research projects (Aradóttir et al., 2015).

The steam accounts for 99.5 % of the emissions. The remaining 0,5 % are gasses such as $CO_2$, $H_2S$ and $H_2$. The gas mixture form the power plant is pumped into a scrubbing tower near the bottom with 35 kg/s geothermal steam condensate, containing no dissolved elements except small amount of $CO_2$ and $H_2S$. The main components of the geothermal gas have very different solubility in water. The sour gases $CO_2$ and $H_2S$ possess much higher solubility in water than hydrogen therefore dissolving readily in the condensate with hydrogen being vented at the top of the scrubbing unit. The condensate water is subsequently transported in a 1.5 km a plastic pipe to the injection wells,

The condensate water with the dissolved gases possesses a pH value between 3.5 and 4 and is corrosive to the carbon steel. To prevent corrosion of casings the low pH condensate water is piped into the well using a 4” stainless steel pipe to depth below casing. This prevents any contact between the carbon steel and gas charged condensate. Between the inner stainless steel pipe and the casing geothermal brine is injected into the well. The brine is 60-80°C and has a pH of 9.3. The two fluids mix at the exit of the stainless steel pipe. The main feed zones in the injection wells are near the bottom of the wells between 1900 and 2200 m. No accurate temperature measurements are available from the injection well but temperature in nearby well is 240-250°C.

Alteration minerals like calcite ($CaCO_3$) and pyrite ($FeS_2$) are common in geothermal reservoirs. They are formed through natural processes where $CO_2$ and $H_2S$ gases form minerals through reaction with the rocks. The same processed take place in the CarbFix-SulFix project where these gasses are injected into the reservoir.

Injection of $CO_2$ and $H_2S$ on an industrial scale started in June 2014 injecting about 30% of the gases from the power plant (Figure 3). The injection capacity is around 14.5 and 7.9 tons/day for $CO_2$ and $H_2S$ respectively. At the end of the year 2015 total 9820 tons of gases had been injected, 6290 tons $CO_2$ and 3530 tons $H_2S$. It has been estimated from monitoring program by using conservative traces that about 75-80% of the $H_2S$ that is reinjected into the geothermal system in the SulFix project at the Hellisheidi is sequestered in the form of minerals like pyrite within six months.

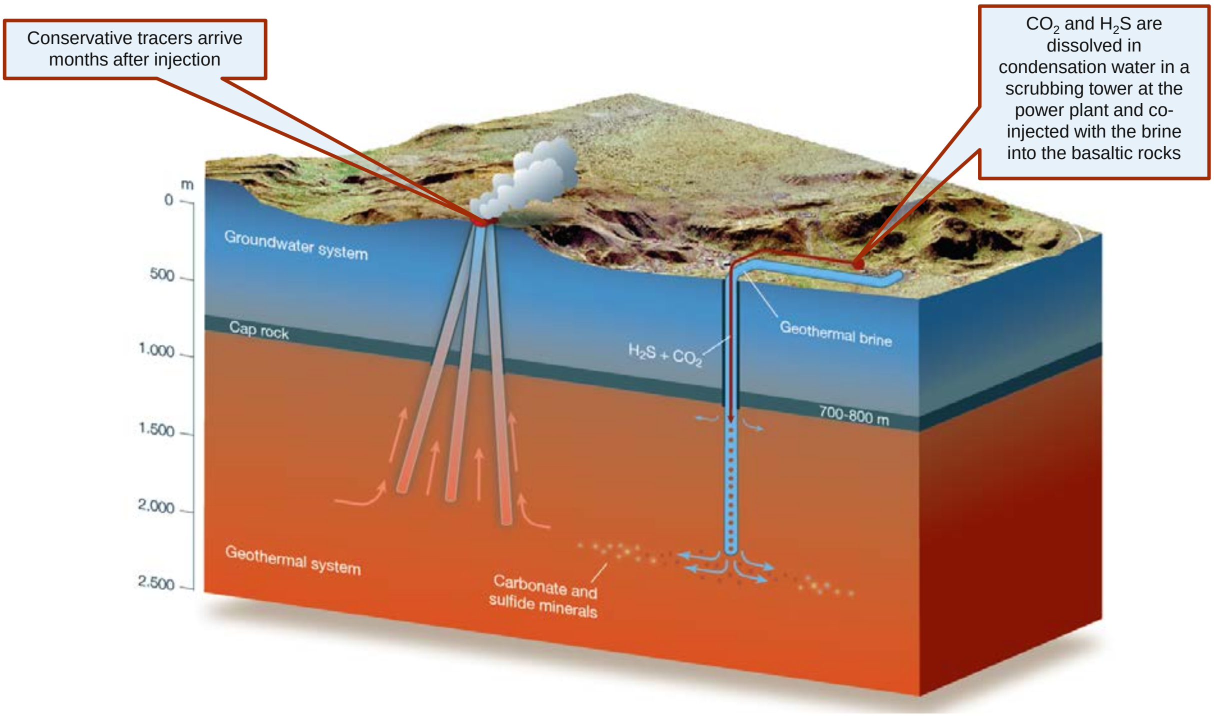


FIGURE 3: Schematic layout of CarbFix-SulFix project at Hellisheidi (from Ingvi Gunnarsson)

The total cost of CarbFix and SulFix injection at Hellisheidi has been estimated to be about 28.2 $/ton sour gas injected. The cost of $CO_2$ capture by using conventional CCS methods is $62-$131/ton $CO_2$ and the cost of conventional S abatement is $356/ton. The economy of CarbFix and SulFix injection is further strengthen its use for reducing gas emission from power plants in Iceland.

## 5. CONCLUSION

The tailor designed monitoring programme for the Nesjavellir and Hellisheidi power plants is a necessary tool to manage the geothermal reservoir and to map its response to utilization. The data collected is used to calibrate numerical prediction models of the geothermal field. It is also the key to solve most problems which may come up in the operation.

Environmental monitoring aims to minimize the impact of the power plant to the nature. Regular data collection show early changes which can be dealt with in time.

The CarbFix and SulFix projects have proved to be successive methods to reduce emission of $CO_2$ and $H_2S$ to the atmosphere.

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