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NESJAVELLIR CO-GENERATION PLANT, ICELAND. FLOW OF GEOTHERMAL STEAM AND NON-CONDENSABLE GASES.

Gestur Gíslason
Orkuveita Reykjavikur, Sudurlandsbraut 34, 108 Reykjavik, Iceland

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ABSTRACT

The monitoring of steam production from the Nesjavellir geothermal field for the Nesjavellir combined heat and power plant (CHP) is carried out by recording flow rates of steam and water at various discharge points, as well as analysing the geothermal gases released into the atmosphere and shallow groundwater.

Operation of the Nesjavellir power plant started in 1990. Annually 5 – 6 million tons of water and steam were extracted from the field, and since 1999 about 10 million tons. Initially the average enthalpy was 1700 kJ/kg, but decreased slowly to 1450 kJ/kg due to the exploitation of the field. Presently the enthalpy is rising again. Today, about 50-75% of the thermal energy of the geothermal fluids is used in the co-generation power plant to produce water for district heating and electricity generation.

The main non-condensable gases in the steam are CO_2 and H_2S. Presently 12000 tons of CO_2 and 3400 tons of H_2S are discharged from the plant per annum. About 90% of the CO_2 and 75% of the H_2S are released to the atmosphere. Comparison with alternative energy sources shows that the geothermal power production at Nesjavellir is relatively environmentally friendly, the average mass of gases per energy unit is 7.2 g CO_2/kWh and 1.3 g H_2S/kWh.

1. INTRODUCTION

The Nesjavellir Geothermal Field is a high enthalpy geothermal system within the Hengill Central Volcano in south-western Iceland. Geothermal investigations at Nesjavellir commenced in 1946, however, it was not until 1986 that a decision was made to harness the geothermal heat for district heating in Reykjavík (Gunnarsson *et al*. 1992). By 1990, 14 production boreholes had been drilled, and all except one were successful. That year the Nesjavellir power plant was commissioned, generating about 100 MW_t, by producing about 560 l/s of 82°C hot water for district heating. Due to the chemical composition of the geothermal water it cannot be used directly. Cold groundwater is therefore heated in the power plant in heat exchangers, using both geothermal water and steam. Initially only four geothermal wells were connected to the plant, but gradually more wells have been connected as the capacity of the power plant has been increased. In 1995 the capacity was expanded to 150 MW_t and in 1998 to 200 MW_t and the production of 60 MW_e of electricity commenced. Presently 10 boreholes are being utilised for the Nesjavellir plant.

2. GEOTHERMAL SYSTEM

The depth of the production boreholes at Nesjavellir ranges from 1000 to 2200 m, and the temperature in the production zone is 320 - 360°C. The characteristics of the wells vary, initially the enthalpy of the fluid ranged from 1500 – 2600 kJ/kg, but the enthalpy has since been influenced by utilisation. From the boreholes the geothermal steam and water in two phase flow is brought to the separation station. (Ballzus *et al*. 2000).

3. POWER PRODUCTION

The co-generation power plant has two functions. The first is to produce electricity with the geothermal steam. The second is to heat cold groundwater for district heating. Figure 1 shows the general design of the plant, but a detailed description is given by Ballzus *et al*. (2000). The first step is to separate geothermal water and steam. Initially the separation pressure was 14_g bar (198°C), but when electricity production began in 1998 the separation pressure was lowered to 12 bar_g (192°C). The water and steam is piped separately to the power house, but excess steam is released into the atmosphere through a high chimney by a control valve which maintains a constant pressure in the steam supply system. A similar system controls the hot water supply to the power house. The excess water boils to atmospheric pressure after the control valve, and the steam formed is released into the atmosphere. The effluent water is discharged into a nearby stream.

Electricity is generated by two steam turbines, each 30 MW, requiring 115 kg/s of steam in total at a pressure of 12 bar. The steam is condensed in a tubular condenser and cooled to approximately 55°C with cold groundwater. The condensate is disposed of in shallow boreholes in the nearby lava field. The cooling water is pumped from a shallow fresh-water aquifer in the lava field 6 km away from the power plant. The temperature of the cooling water is 5-7°C. About 1200 kg/s of cold water is required for the condensers. The cooling water is heated to about 55°C in the condensers, and then piped through heat exchangers, for final heating to 87°C, using the 192°C hot geothermal water from the separators. In the heat exchangers the geothermal water is cooled to 55°C, and discharged into a stream. By degassing under vacuum in the deaerators the dissolved oxygen is removed from the heated water. The final treatment before the water is pumped to Reykjavík for district heating is to inject some geothermal steam, both to remove the last traces of dissolved oxygen by its reaction with the hydrogen sulphide (H_2S) in the steam, and to adjust the pH of the water to pH 8.5 (Ballzus *et al*. 2000).

Before electricity generation started in 1998, the steam was only used for the district heating plant. At that time the heat extraction from the steam phase was more efficient, the temperature of the condensate effluent was about 9°C compared to the present 55°C.

4. METHODS

Most of the measurements needed to make the flow rate and energy flow calculations for this study are recorded in the centralised control and monitoring computer system. There are, however, a few measurement which have to be recorded manually. Since September 1994 this has been done weekly, and the calculations in this paper are based on those records.

The chemicals discussed in this study are limited to two components, carbon dioxide (CO_2) and hydrogen sulphide (H_2S). Samples of the geothermal steam and water as well as the condensate are collected monthly for analyses of gases. Samples for total analyses of water and steam are collected twice a year. The concentartions of the geothermal components vary as different boreholes are in use depending on the power plant load. The chemical composition of the cold ground water is fairly constant, and samples are taken twice a year.

The following discussion on disposal of water and gases takes only into account the flow which passes through the flow lines of the power station. Releases during testing of wells are not included, but this is minimal except in 1996, when extensive well flow tests were carried out in preparation for the expansion of the power plant.

5. FLOWS – SANKEY DIAGRAMS

5.1 Well discharge

Figure 2 shows the total flow rate of steam and water from the field as measured in the separation station. The lower area shows the rate of water discharge and the upper area the steam flow rate. The first noticeable feature is the “noise” on the curves. This can be partially accounted for by different wells being connected to the separation station and partially by inaccuracies in the measurements. The graph shows periods when power production was stopped for maintenance and one or two occations in the summer when the steam gathering system was stopped. A major expansion of the power plant was carried out in 1998, which is reflected in the graph that year as a long stop in production. Before the production of electricity commenced, the well discharge was governed by the production of water for district heating. This can be seen on the graph, high discharge rate during the winter months and a low discharge rate during the summer months. In 1998 co-generation of electricity and water for space heating started, and since then the steam requirements of the turbines dictate the well flow, which is constant at 115 kg/s of steam at 12 bar_g. The characteristics of the field governs the amount of geothermal water accompanying the steam, although this can be influenced to some extent by choosing different wells, as their steam/water ratio varies. As can be seen on the graph, the summer/winter variation in well discharge is less prominent after co-generation started. The total discharge increased dramatically in 1998, as the number of connected wells was doubled from five to ten wells to meet the increased demand for steam. In October 1999 only one turbine was in operation, explaining lower discharge during that time. Table 1 shows the total annual mass discharge from the boreholes. The data for 1994 does not include the whole year as indicated by the number of months in column 2. The total volume of hot water for district heating is also shown. It was fairly constant in 1995 – 1997 and 1999, but less so in 1998, due to the long production stop.

In this paper Sankey diagrams are used to describe the flow through the plant. Figure 3 shows the mass flow, figure 4 the energy flow and figure 5 the flow of non-condensable gases. All the diagrams represent the situation on March 31, 1999. The main mass flow (figure 3) is the cold groundwater, which is used for cooling in the steam condenser, and is then either pumped to Reykjavik for district heating after final heating to 82°C and adjustment, or released into a stream as excess cooling water. The mass flow from the geothermal boreholes is much smaller than the fresh-water flow, and it is disposed of at several discharge points in the plant.

5.2 Heat Content - Enthalpy

The steam/water ratio at a given separation pressure enables the calculation of the average enthalpy of the geothermal fluid. The results from those calculations are shown in figure 6. The general trend shows a rapid decline in enthalpy, from 1700 kJ/kg in 1994 to about 1450 kJ/kg in late 1997. From that time the enthalpy has remained fairly constant until mid-1999 when it rose again. From 1990 to 1995 only four wells were connected to the steam supply system. All these wells are located in the western part of the field and had initially high enthalpy, up to 2600 kJ/. The wells in the eastern part have on the other hand enthalpy in the range of 1300 – 1500 kJ/kg. In 1995 the fifth well was connected, and in 1998 an additional ten. These wells have lower enthalpy than the first 4 wells, and cause some of the changes seen in figure 6, but the main reason for the decline of the enthalpy is that the enthalpy of individual wells started to fall shortly after utilisation commenced. This was particularly true for the wells which initially had the highest enthalpy (Steingrimsson *et al*. 2000). In 1988 the first reservoir model calculations of the Nesjavellir geothermal field was presented. This model has been updated twice with minor adjustments made (Bodvarsson *et al*. 1991, Bodvarsson *et al*. 1993). The first model indicated this drop in enthalpy fairly accurately, and an interpretation of the chemical monitoring data of the geothermal fluids indicates that the drop in enthalpy is caused by an inflow of lower enthalpy fluid from the eastern part of the field (Gunnlaugsson and Gislason 1997). The subsurface temperature is similar in both parts of the field, well in excess of 300°C. The flow of steam has remained constant from the boreholes, and the enthalpy drop is caused by increased flow of geothermal water and therefore increased total discharge. This can be seen in figure 2 as the steam portion of the graph is fairly constant during 1994 through 1997, but the water flow increased from year to year as did the total flow. Apparently the utilization from late 1998 of the eastern wells stopped the flow of lower-enthalpy fluid towards west. The decreased water discharge (but constant steam) in 1999 (figure 2) shows that the western side of the field is recovering from the inflow.

5.3 Energy Flow and Efficiency

The Sankey diagram in figure 4 is calculated from the flow rate and heat content of water and steam. It shows the situation at the same time as figure 3. The main energy input comes from the geothermal field, and is evenly distributed between steam and water. Energy from the steam is transferred in the generator and condenser to generate electricity and to heat water. In the heat exchangers geothermal water is used to complete the heating of water for space heating. The diagram shows that energy is wasted at several discharge points in the flow line. The steam portion is very efficiently used in the turbine/condenser, producing steadily 60 MW_e of electricity and 1200 kg/s of 55°C hot water (245 MW_t). The demand of heated water for space heating differs seasonally, it is highest during winter as shown in figure 2, but during summer it may be as low as 50% of the peak demand. The availability of geothermal water is controlled by the need for steam for electricity generation but its use is directly linked to the demand for heated water. The result is that considerable energy is lost by disposing of excess cooling and geothermal water (figure 4).

The lowest part of figure 7 shows the total energy flow through the power plant from 1994 to 1999. Also shown is the energy which is transferred over to the cold water, and, after October

1998, to the electricity production. The difference (light coloured) reflects the energy which is not used.

The lower part of figure 7 also shows the total energy flow from 1994 to 1999 through the power plant, calculated from a base temperature 0°C. The energy is devided into three areas, the energy in the heated water; the electricty production, starting in October 1998; and the energy which is not used. Most of the energy not used is released into the atmosphere through the chimeys, but some of it is in the cooled waste water and condensate from the plant. The temperature of the waste water depends on the design of the plant and its operation; recently its temperature has been 55 – 60°C.

Efforts have been made to minimize the energy wasted through the chimneys. The top part of figure 7 shows how much of the energy from the borefield is used to heat water and for electricity production. The base temperature is the temperature of the waste from the plant. From 1994 through 1997 this ratio lay between 50 and 75%, falling slightly during the period. At the time the separated water was only used in the production line for a small scale pilot testing of heat exchanger. Utilisation of the water phase is problematic due to precipitation of silica, but based on the pilot studies, new types of heat exchangers for the separated water were designed and installed in December 1997, improving the efficiency of the process, bringing it close to 75%. Due to this improvement less water and steam was required from the borefield (fig. 2) for the same production.

After the addition of the electricity plant in the summer of 1998 the energy extracted from the reservoir increased over 50% while the output from the plant only increased about 30% (fig. 7). As discussed earlier, this is mainly caused by the fact that the electricity production is constant and not synchronized with the hot water production. The energy transfer from the geothermal to heated water and electricity is now in the range of 30 – 75%, but at the same time the base temperature (i.e. the temperature of the condensed steam) is now about 55°C compared to 9°C originally. The energy in the waste has therefore increased. It is clear the use of energy can be improved, but the co-generation at Nesjavellir makes the efficiency of the plant higher than is generally achieved in geothermal power plants which only generate electricity.

6. NON-CONDENSABLE GASES

6.1 Gas Flow Rate

The mineral content of the geothermal fluids of the Nesjavellir geothermal system is in the range of 1000 – 2000 mg/kg which is fairly low compared to most other high enthalpy geothermal systems, but considerably higher than the local cold ground water. In a two phase flow, most of the mineral components reside in the water phase. The main components which are distributed between the water and steam phases are carbon dioxide (CO_2) and hydrogen sulphide (H_2S). These two gases will be discussed in this section of the paper.

Samples are collected monthly of the geothermal water and steam for the analysis of the non-condensable gases. In the steam heat exchanger and later in the condenser, gas separation takes place as the steam condenses. Samples of the condensate are collected for analysis. Vacuum pumps extract the gas from the condenser, which is then released to the atmosphere in a tall exhaust chimney at the power station. De-gassing also occurs when the excess geothermal water boils. About 10% of the carbon dioxide and 20% of the hydrogen sulphide remain in the waste geothermal water phase after boiling. As the chemical composition of the cooling water is stable, samples are collected twice every year, but the composition of the heated water is analysed more frequently, H_2S and pH are measured daily.

The monitoring of flow rate and chemical content enable the calculation of the total amount of gases brought to the surface from the geothermal reservoir through the boreholes, and to follow their path through the plant and map the release point. Figure 8 shows the amount of CO_2 and H_2S from the borefield in tons per annum. The amount is directly linked to the flow of steam and water from the boreholes. A marked increase in gas release occurred after electricity production started. From 1994 to 1998 the annual release was about 7000 tons of CO_2 and 2000 tonnes of H_2S per annum respectively, but closer to 12000 tons and 3400 tons in 1999.

Figure 5 is a Sankey diagram of the flow of non-condensable gases in the Nesjavellir power plant. It shows that about 95% of the gases from the boreholes are released into the atmosphere. Monitoring of H_2S in atmosphere at Nesjavellir (Ivarsson *et al*. 1993) confirms that the concentration is highest close to the power house, but there is a great variation in concentration of H_2S at the same measuring pointsat different times, depending on the weather. Concentration was measured at 22 points, covering an area of 8 km^2 around the plant.

CO_2 and H_2S are natural components of high enthalpy geothermal systems, and measurements at fumaroles and steam vents at Nesjavellir geothermal field show that the average concentration of these gases in the natural steam is 10 g/kg CO_2 and 1,2 kg/kg H_2S (Ivarsson 1998). Measurement of steam flow and gas release from the thermal manifestations suggests that the total natural release of these gases into the atmosphere is minimum 750 tons per annum, and is probably in the range of 3000 – 4000 tons (Gislason 1998).

6.2 Greenhouse gases

The release of carbon dioxide, one of the greenhouse gases, is of concern due to its negative impact on the environment. The rate of release is considerable, about 12000 tons per annum, and studies are being made to improve the situation. On the other hand, the energy production at Nesjavellir is relatively clean compared to other energy sources. To compare different energy sources the rate of release of greenhouse gases is calculated per energy unit (g CO_2/kWh). With co-generation of electricity and hot water for space heating at Nesjavellir the value is 7.2 g CO_2/kWh (table 2), and on figure 9 this is compared to the alternative sources (Armannsson and Kristmannsdottir 1992). The difference between electricity production (Krafla power station NE Iceland) and space heating using high enthalpy systems (Nesjavellir before 1998) is in favour of the latter. This is partially due to the more efficient use of geothermal energy and partially due to different chemical compositions of the relevant geothermal systems. The high value for solar energy is based on the use of ranking cycle steam system, which uses natural gas to meet peak demand. The use of fossil fuel is in all cases much less environmentally friendly than geothermal energy (Armannsson and Kristmannsdottir 1992).

The main alternative to geothermal energy in Iceland, is the abundantly available hydro power. Its use does not release any greenhouse gases directly, however, main negative environmental impact for hydro power is the large areas of land which are required for reservoirs. There is a growing awareness in

Iceland to maintain the inland wilderness, which is also important for the Icelandic tourist industry.

The operator and owner of the Nesjavellir power plant is Orkuveita Reykjavikur (Reykjavik Energy), which supplies hot water for space heating as well as electricity and water to the capital of Iceland, Reykjavik and its neighbouring communities, a total of 160,000 inhabitants. Only a part of the hot water comes from the Nesjavellir power plant, most of the water is pumped from four low enthalpy fields within or close to the city. These areas are free of CO_2-emission, and the CO_2-co-efficient for the whole operation of Orkuveita Reykjavikur is 1,4 g/kWh.

Use of geothermal water for space heating in Reykjavik firststarted in 1930. At that time all houses were heated by burning fossil fuel. Since 1930 geothermal has replaced the use of imported coal and oil, and now over 99,9% of houses are heated by geothermal energy. This has reduced the emission of CO_2, and figure 10 shows the reduction of CO_2-emission due to the use of geothermal energy by Orkuveita Reykjavikur.

6.3 Hydrogen Sulphide Emission

Hydrogen sulphide has a very distinct smell, which is characteristic for all high enthalpy areas with surface manifestations. There is a concern that H_2S oxidises to SO_2, causing acidification to rain and soil (Kristmannsdottir *et al*. 1999). Studies indicate that this process is highly dependant on the local weather conditions. The main process in converting H_2S to SO_2 in the atmosphere is photo-oxidation. H_2S is efficiently removed from the atmosphere by rainfall, and it is well known that close to fumaroles the H_2S is oxidised to sulphur, which may be beneficial to the environment when it reacts with the soil. Extensive studies of this process in Iceland indicate that a minor conversion of H_2S to SO_2 occurs at atmospheric conditions in Iceland (Kristmannsdottir *et al*. 1999).

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Year	Months	Discharge Tonn*10^3	Production Tonn*10^3
1994	3	1219	4045
1995	12	4963	15528
1996	12	5717	14331
1997	12	6456	15266
1998	12	4231	8445
1999	12	10470	14646

Table 1. Total discharge of geothermal fluid and the production of heated water for space heating

Bodvarsson, G.S., Bjornsson, S., Gunnarsson, A., Gunnlaugsson, E., Sigurdsson, O., Stefansson, V. and Steingrimsson, B. (1991). The Nesjavellir geothermal field, Iceland. *Geotherm. Sci & Techn., Vol. 2(4) pp. 229-261.*

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Ivarsson, G., Sigurgeirsson, M., Gunnlaugsson, E., Sigurdsson, K.H., and Kristmannsdottir, H. (1993) *Measurement of gas in atmosphere. Concentrations of hydrogen sulphide, hydrogen dioxide and mercury on high temperature fields.* Hitaveita Reykjavíkur and Orkustofnun, OS-93074/JHD-16. Unpupblished report, in Icelandic.

Kristmannsdottir, H., Sigurgeirsson, M., Armannsson, H., Hjartarson, H., and Olafsson, M. (1999). Sulphur Emission from Geothermal Power Plants in Iceland. *Geothermic, in press.*

Steingrimsson, B., Bodvarsson, G.S., Gunnlaugsson, E., Gislason, G. and Sigurdsson, O. (2000). The Nesjavellir High Geothermal Field, Iceland. World Geothermal Council 2000 (this issue).

Hot water	
Average flow rate	700 kg/s
Temperature of heated water	82°C
Average return temperature	32°C
Average energy output	147 MW_t
Electricity	60 MW_e
Total energy	207 MW
Steam	
Average steam flow	126 kg/s
Average CO2 concentration	3,3 g/kg
Average release of CO2	416 g/s
Emission of CO2 from plant	**7.2 g/kWh**

Table 2. Calculation of CO_2-emission from the Nesjavellir plant

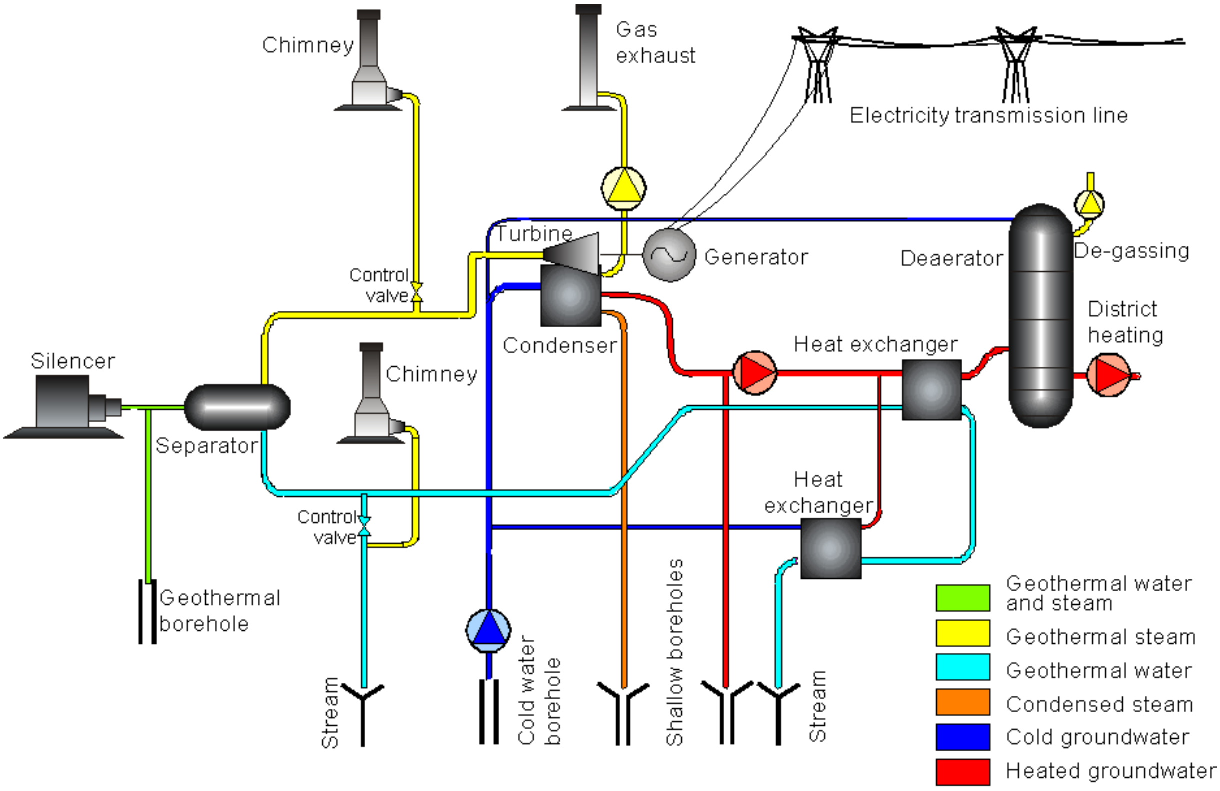

Figure 1. Design of the Nesjavellir plant

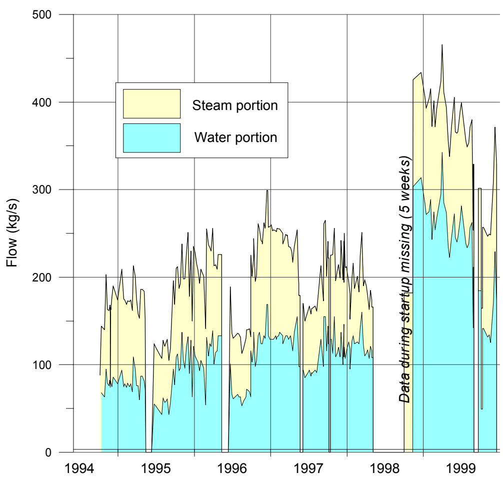

Figure 2. Total mass discharge from the Nesjavellir field

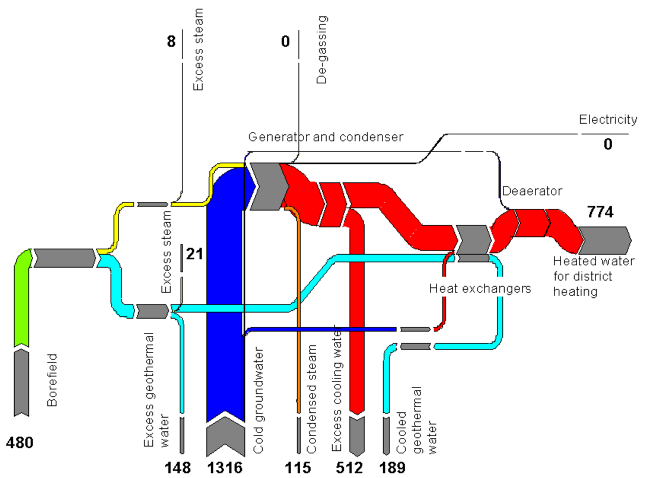

Figure 3. Sankey diagram, mass flow (kg/s) on March 31, 1999. (For legend see figure 1)

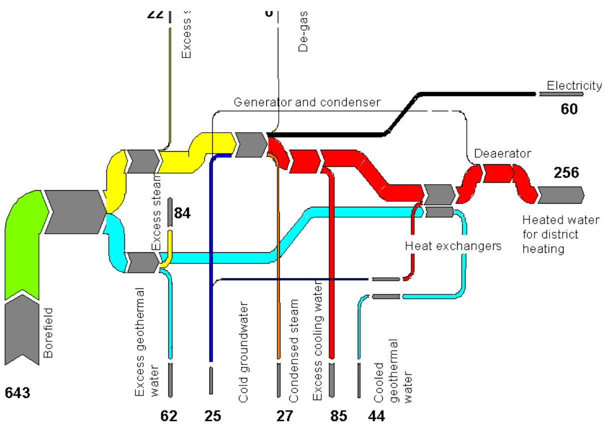

Figure 4. Sankey diagram, energy flow (MW) on March 31, 1999. (For legend see figure 1)

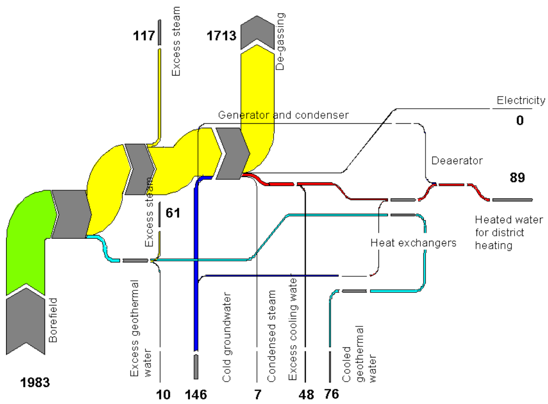

Figure 5. Sankey diagram, non-condensable gases. Figures represent the sum of CO_2 and H_2S (kg/h) on March 31, 1999. (For legend see figure 1)

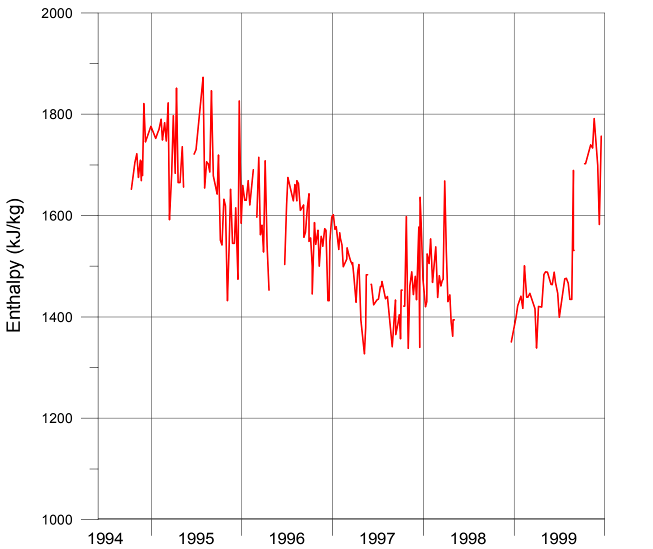

Figure 6. Enthalpy of well discharge from Nesjavellir – Average for all wells

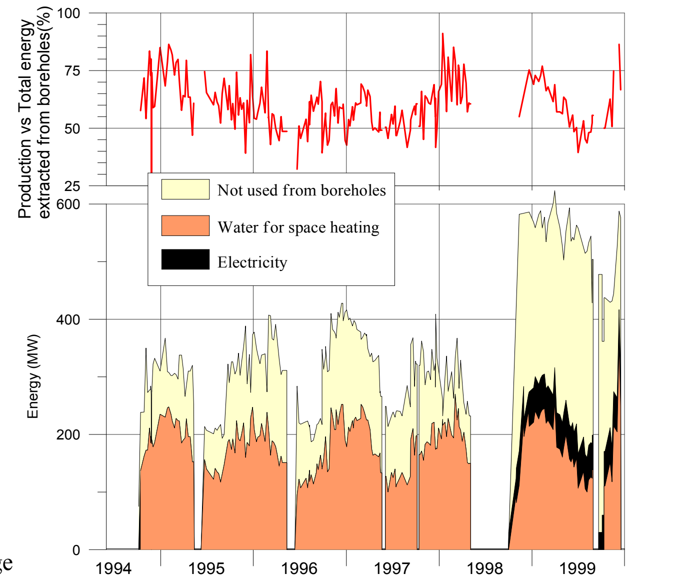

Figure 7. Total energy flow from geothermal field and cumulative energy of heated water and electricity. Production vs total energy ratio (%) at top

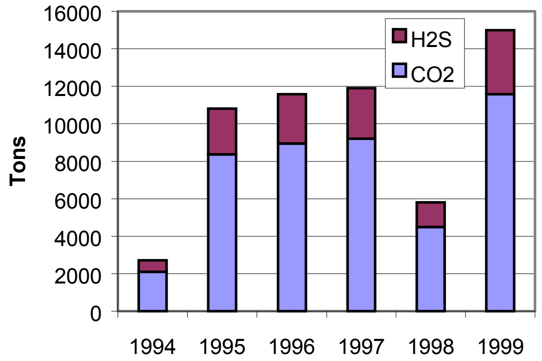

Figure 8. Total amount of non-condensable gases released per annum (figures for 1994 is for 3 month)

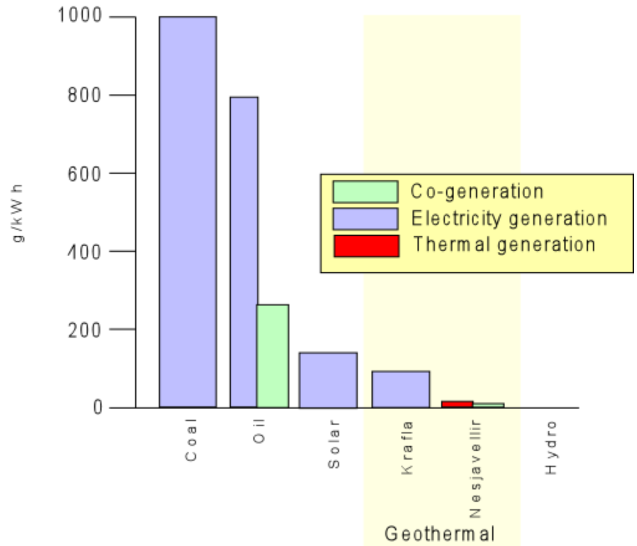

Figure 9. Emission of greenhouse gases from different energy sources

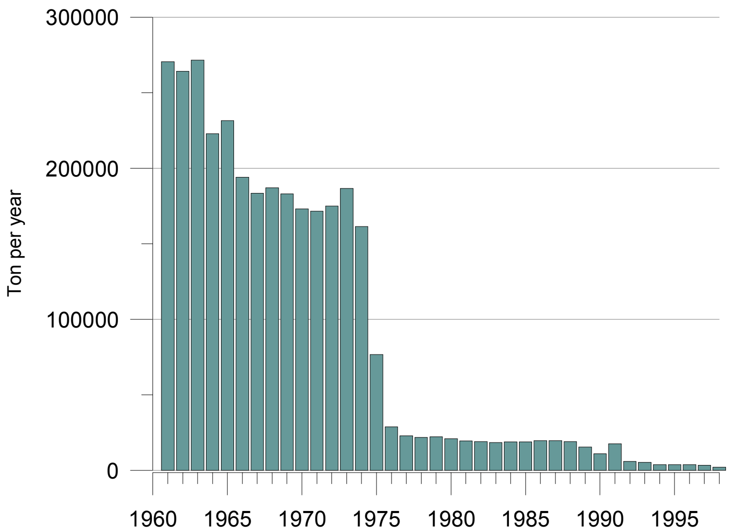

Figure 10. Reduction of carbon dioxide emission in Reykjavik due to introduction of geothermal heating