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Utilization of Low Temperature Geothermal Systems at Dalvík, North Iceland, and Egilsstadir and Fell, East Iceland

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ABSTRACT

The evolution of low temperature geothermal systems due to domestic utilization in two different parts of Iceland is introduced. The geothermal system at Urridavatn provides the villages Egilsstadir and Fell and their surroundings in E-Iceland with geothermal water for heating and domestic use and two separate low temperature geothermal systems, Hamar and Birnunesborgir, provide the same to Dalvík, a village in N-Iceland and the surroundings. In each of the systems two wells are the main production wells, or one well and a reserve well. These systems have been monitored for several decades, such as their production, drawdown and the temperature of the water entering the distribution systems. These geothermal systems in two different parts of the country have managed to provide sufficient geothermal water to the communities in spite of increasing needs. New wells have been drilled to meet increased needs of the customers and expanding distribution systems and group of customers. In Urridavatn the newest well was connected to the distribution system in 2007 and has with the previous main well provided sufficient water to the community at Egilsstadir-Fell and the temperature in the system has been stable from 2007. The production from Hamar provided geothermal water for Dalvík and surroundings from 1969 and in 1997 production stared at Birnunesborgir for the communities south of Dalvík. The two systems were partly joined when in 2006 the increasing needs for Dalvík were met by adding a little of the 10°C warmer water from Birnunesborgir to the water from Hamar, thereby also increasing the temperature of the water to Dalvík by 2°C and keeping the necessary flow rate. Water from Birnunesborgir has since 2007 also been used for distribution to Svarfadardalur, south and west of Dalvík.

1. INTRODUCTION

The evolution of low temperature geothermal systems during utilization in two different parts of Iceland is introduced. Hitaveita Dalvíkur (HD) and Hitaveita Egilsstada og Fella (HEF) started operation in 1969 and 1979, respectively, and have provided geothermal water to the inhabitants at Dalvík, Árskógssandur, Hauganes (Figure 1), North Iceland, and their surroundings, and Egilsstadir and Fell, East Iceland, and its surroundings. Monitoring was limited in the beginning of their operations but it was soon realized how important it is to be able to view data for seeing the evolution of the boreholes themselves and the geothermal system in their close vicinity and use the information for decision making in managing the resources.

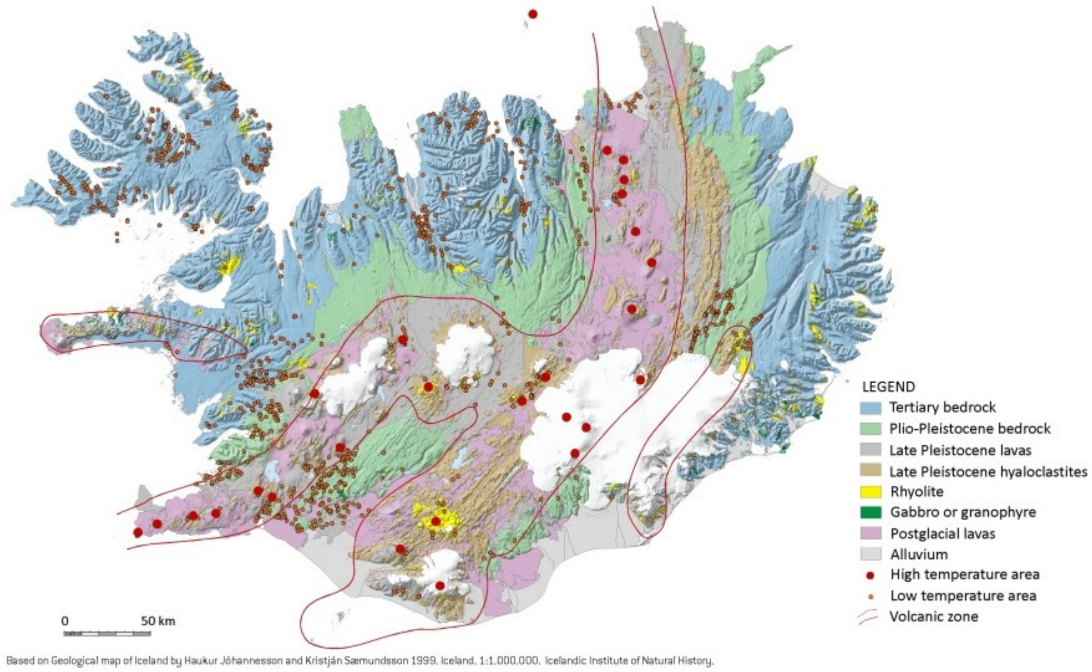

Figure 1. A geological map of Iceland showing the volcanic zones, surrounded by red lines. Geothermal activity is shown as big red dots for high temperature areas and smaller red dots for low temperature areas.

Figure 1 shows a geological map of Iceland where the volcanic zones are circled with red lines and geothermal areas are shown as dots. High temperature systems are within the volcanic zones and the low temperature systems are normally around these zones as well as spread out in different parts of the country.

The web of the Icelandic Meteorological Office (Vedurstofa Íslands, 2014) shows that the 30 years average temperature from 1961 to 1990 for Reykjavík is 4.3°C where the average temperature in July for those 30 years is 10.6°C. The variation between years is not great and most other parts of the country are colder than Reykjavík so clearly space heating is important during the whole year. The natural resources of Iceland are mainly the hydropower and geothermal energy and they are probably among the main reasons for the standard of living in the relatively harsh climate and nature of the country, with a population of approximately 325,000 inhabitants (March 2014).

Over two hundred utility companies providing hot water for space heating and domestic use are operated in Iceland and most of them use almost entirely geothermal energy as their heat source (Oddsdóttir and Ketilsson, 2012). The geothermal energy supplies about 89% of the requirements for space heating in Iceland and most of it is provided by low temperature (LT) systems, which are defined as systems where the temperature is below 150°C at 1000 m depth. High temperature (HT) systems are by definition where the temperature at 1000 m depth is above 200°C and they are mainly used for electricity production. The HT systems are additionally used indirectly for space heating, i.e. cold groundwater is heated up by the geothermal water to avoid scaling and corrosion and the same applies for some of the LT systems depending on their dissolved chemicals.

The evolution in the geothermal systems at Hamar and Birnunesborgir utilized by Hitaveita Dalvíkur, will be introduced as well as the evolution in the geothermal system under and in the surroundings of Urridavatn utilized by Hitaveita Egilsstada og Fella.

2. GEOTHERMAL SYSTEMS IN ICELAND - UTILIZATION

The first formal geothermal space heating company, Hitaveita Reykjavíkur (at present Orkuveita Reykjavíkur), started operation in 1930 in Reykjavík when geothermal water was provided for central heating and domestic use in several homes and official buildings.

Most of the utility companies providing space heating are named “hitaveita”, which signifies the provider of heat (hiti=heat, veita=provider) although they may have different other operations, e.g. cold water distribution and sewage services, which is indeed the case for the geothermal utility companies whose production will be introduced in this paper, Hitaveita Egilsstada og Fella and Hitaveita Dalvíkur.

The geothermal system at Hamar was studied previously by Axelsson et al. (2005) where they write: “The Hamar system appears to have been utilized in a sustainable manner during the last three decades. The production history is too short, however, to establish whether the current level of utilization is sustainable according to the definition above”. The definition for sustainable geothermal utilization was based on the Bruntland’s report (World Commission on Environment and Development, 1987): “development that meets the needs of the present without compromising the ability of future generations to meet their own needs”. Axelsson et al. (2005) define sustainable utilization of a geothermal resource as using the resource at a certain rate for a very long time, 100-300 years. Modeling was therefore used to estimate whether the system at Hamar was being utilized in a sustainable way. A lumped parameter semi-open model predicted that the pressure changes for a 200 year production history with average production of 40 kg/s would be within the given limits of sustainability. In the same study another model was used to find the time of replacing the water storage. This showed to be 15-45 years, so in case of an open reservoir cold water could replace the warm water. Therefore the energy content would rather limit the system at Hamar than the pressure draw down, while not exceeding 40 kg/s production. Axelsson et al. (2005) show that the production limit, 40 kg/s, has still not been reached, the average production is approximately 30 kg/s. Without going into details it may also be mentioned that with a simple model they show that the cold front breakthrough would not occur until after more than 200 years even with their lower limit of reservoir volume in the model, 0.5 km^3.

The potential of a geothermal system to produce energy is primarily limited by pressure decline, or draw down caused by utilization, and also by available energy content in the system (Axelsson et al., 2004, 2005). The life time and efficiency of a geothermal system without over exploitation during utilization depends mostly on fissures providing good permeability, available water and the heat source. Sustainable management of the resource is clearly of great importance while aiming at using the system for a long period of time. Monitoring utilization, pressure or water table and temperature of the geothermal water from each well is important for analyzing and following the evolution of the geothermal system.

3. DALVÍK AND SURROUNDINGS - GEOTHERMAL UTILIZATION

3.1 The Hamar and Birnunesborgir Geothermal Systems, N-Iceland

The municipal utility company, Hitaveita Dalvíkur (HD), provides geothermal water for heating and domestic use as well as industries in Dalvík, Árskógssandur, Hauganes, Svarfadardalur and their surrounding communities (Figure 2). Approximately 850 customers in over 90% of the households, with a total of 1800 inhabitants, utilize the services of HD.

Hamar in Svarfadardalur and Birnunesborgir south of Dalvík are low temperature geothermal systems in N-Iceland (Figure 2) providing geothermal water for Dalvík, Árskógssandur, Hauganes and surrounding districts. The geothermal system at Hamar has been utilized from 1969 for heating and domestic use at Dalvík, whereas the geothermal system at Birnunesborgir has been utilized from 1998 for Árskógssandur and Hauganes as well as industrial areas in their vicinity. The main industries are drying fish and making the known delicacy Icelandic “hardfiskur”. In December 2007 the distribution of geothermal water was extended to Svarfadardalur. During recent years a little of water from Birnunesborgir has also been mixed with the water from Hamar for Dalvík, increasing its energy, both the flow rate and temperature of the mixed water, since the water from Birnunesborgir is over 10°C warmer than at Hamar.

The possibilities of utilizing a geothermal system depend mostly on fissures providing good permeability, available water and the heat source. The Dalvík area lies in an active earthquake zone and the biggest earthquake in recent times had its origin close to Dalvík 8 decades ago, on 2 June 1934, with magnitude of over 6 on Richter scale. The earthquake shook the surroundings causing much property loss but luckily no injuries or fatalities. The prevailing tectonic direction at both Hamar and Birnunesborgir is NNE-SSW and they are in a tectonically active zone, providing fractures for good permeability.

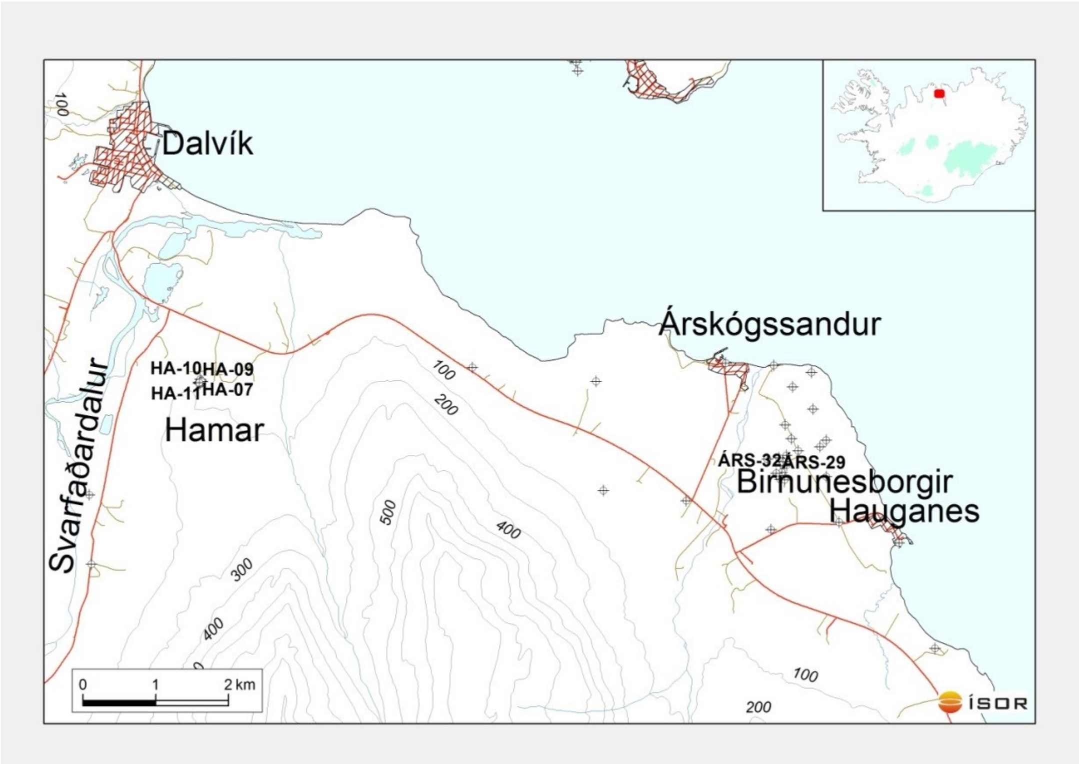

Figure 2. Dalvík, Árskógssandur and Hauganes in Eyjafjördur, N-Iceland. Low temperature systems which are utilized for heating and domestic use are at Hamar in Svarfadardalur and Birnunesborgir. The figure also shows the main wells in both fields.

Investigations in August 1970 at Svarfadardalur, around the geothermal area at Hamar, were made with the purpose of finding a good location for a new borehole, since the last two (HA-3 and HA-4) which had been drilled had not met expectations (Sæmundsson, 1970). Geological studies as well as resistivity- and magnetic soundings were done and the results showed a prevailing NNE-SSW direction of large faults and intrusions as well as a graben. The warmest natural outflow in the area was 14-17°C, which reached the surface at the edge of an intrusion. According to Einarsson (1979) the production at Hamar was 40 l/s of 64°C water in 1979 with less than 20 m draw down. His studies had the aim of checking if it was feasible to extend the distribution of the geothermal water from Hamar to Svarfadardalur and Árskógssandur and surroundings and he deduced that probably the production from Hamar could go up to 60 l/s with increased pumping but drilling a new well would soon be necessary. In Karlsdóttir and Axelsson (1986) an overview of the system is given when 10 boreholes had been drilled of which only 3 had been useful as production wells. Resistivity measurements indicated upwelling of warm water along a NE-SW fracture which lies across where the production zone was located. Magnetic measurements also showed two N-S dykes and from the resistivity measurements warm water was detected along one of them. They deduced that the system could support up to 60 l/s for 20 years with less than 100 m water level draw down or approximately 10 bar, but possibly risking some temperature reduction. In 1977 HA-10 had been drilled after which it became the main production well, producing on the average 40 l/s of 65°C water. Hjartarson and Ólafsson (1999) wrote about the evolution of the field in 1998, where HA-10 had been the main production well at Hamar until in 1988 when HA-11 was drilled and took over as the main well and HA-10 became a reserve well. The boreholes HA-7 and HA-9 are used for water level monitoring. They are not utilized for production and therefore undisturbed by direct pumping, whereas turbulence due to pumping in HE-10 and HA-11 would disturb such measurements.

In 1996 and 1997 (Hjartarson and Ólafsson, 1999), the local authorities of Árskógssandur and surroundings had investigations performed with the aim of finding signs of a geothermal system providing sufficient water to be utilized for the area. From research in the area the most important information was gained by drilling exploration wells, but geological studies and magnetic measurements were also done as a part of the investigations. As a consequence a borehole was drilled in the temperature gradient anomaly where three dykes were believed to intersect each other. In 1997 ÁRS-29 was drilled (Flóvenz et al., 2004) to 440 m depth, providing 16.5 l/s of 74°C water with minor draw down. This was sufficient for the needs at Árskógssandur and Hauganes as well as the industrial and service companies in the surroundings. In 2006 ÁRS-32 was drilled to approximately 900 m depth. The average water temperature from the wells at Birnunesborgir measured by Iceland GeoSurvey (ÍSOR) is approximately 75°C.

3.2 The geothermal systems at Hamar and Birnunesborgir – processing data and results

Data which were analyzed were provided by Hitaveita Dalvíkur and temperature and wind speed at Mödruvellir, an automatic weather station in Eyjafjördur, was provided by Icelandic Meteorological Office. The wind effect was added to the daily average temperature, sometimes called “cooling” rather than temperature (Haraldsdóttir and Hardardóttir, 2012). Figure 3 shows the available data for average daily flow rate at Hamar and the temperature from Mödruvellir including the wind effect, from 2006 throughout 2012, the period which is the main focus of this study. It may be noticed that the data set of flow rate from Hamar was not complete and that the figure indicates an inverse correlation between the flow rate and the temperature. Where the production is low the temperature including the wind effect is high and vice versa. A cross plot showing the flow rate as a function of the temperature including the wind effect is shown in Figure 4 and a relatively good correlation is found. The formula for the flow rate as a function of temperature is used to estimate the missing values of flow rate, which are shown with the monitored data in Figure 5, and used in the dataset throughout the paper. Data prior to 2006 had previously been prepared in a similar way.

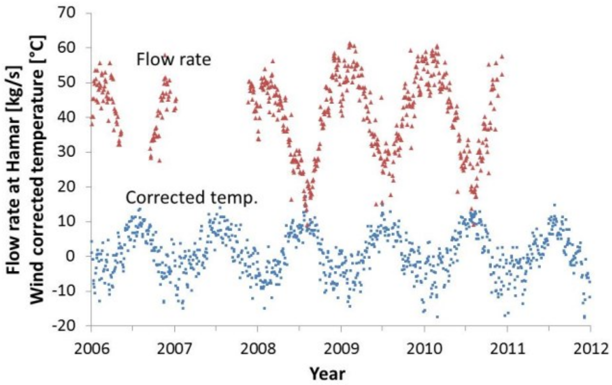

Figure 3. Flow rate at Hamar and temperature including the wind effect from Mödruvellir from 206 to 2011. (Adapted from Haraldsdóttir and Hardardóttir, 2012.)

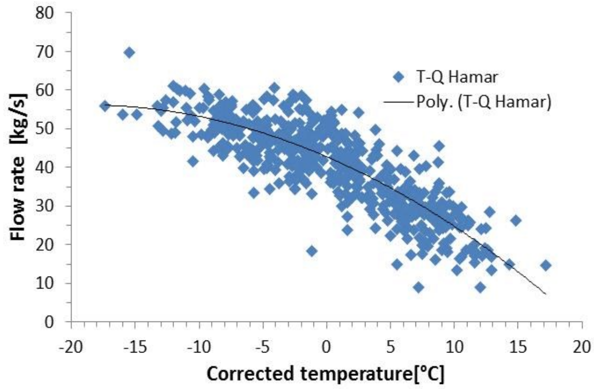

Figure 4. Daily averages of flow rate at Hamar from 2006 to 2011 as a function of temperature at Mödruvellir including the wind effect. (Adapted from Haraldsdóttir and Hardardóttir, 2012)

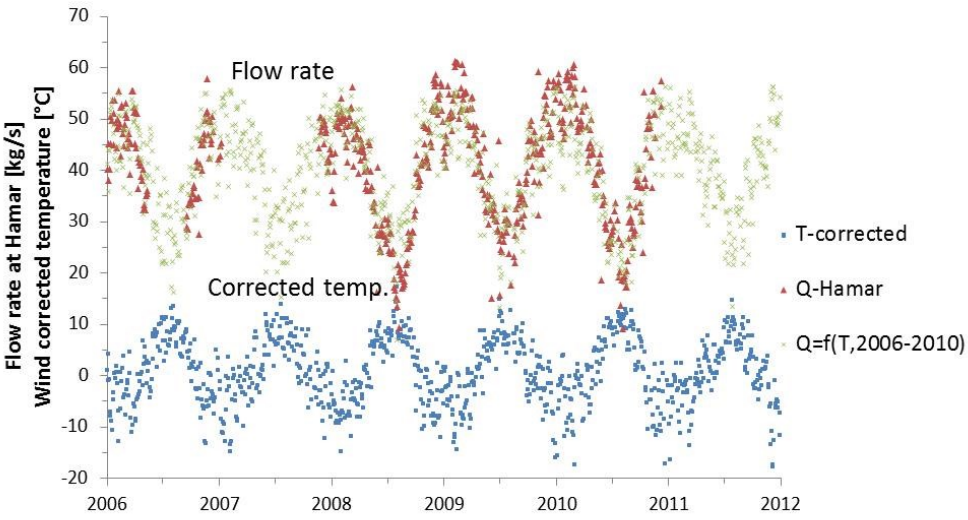

Figure 5. Daily averages of flow rate at Hamar and temperature including the wind effect at Mödruvellir from 2006 to 2011 and calculated flow rate, according to Figure 4, where values were missing in Figure 3. (Adapted from Haraldsdóttir and Hardardóttir, 2012.)

Figure 6 shows water level and the full series of monthly averages of flow rate from 1978 to 2011 at Hamar, which for the first years were calculated from yearly averages of flow rate and monthly averages of temperatures, when there was very little monitoring (Axelsson and Hauksdóttir, 2005). The water level was measured in wells HA-7 and HA-9 since there is no significant difference between the water table in the two wells. The seasonal changes are the main features seen in the figure both for the flow rate and water level where high flow rate causes low water table and low flow rate leads to some recovery of the water table. There is a sudden decrease in the flow rate in 1985 and increase in the water level at the same time due to changes in billing, when flow meters were installed for each household after which less water was wasted. The water level kept on rising more than the corresponding reduction of flow rate but from 1995 the water level has been going down year by year, yet only a total of approximately 30 m or 3 bar which is relatively good for a low temperature system in Iceland (Axelsson 2010, Axelsson et al. 2010). The difference between high and low flow rate per year varies to some extent, and in 2009 the utilization exceeded what it had previously been.

Monthly averages of flow rate and water temperature from 1988 to 2011 at Hamar are shown in Figure 7. The monitored water temperature increased in 2006 and is approximately 1.5°C higher than before during the following years. This is not seen in measurements done during sampling for chemical analysis by employees of Iceland GeoSurvey (ÍSOR). According to the manager of Hitaveita Dalvíkur water from Birnunesborgir was mixed with the water from Hamar. Iceland GeoSurvey (ÍSOR) measures the temperatures during chemical sampling and during recent years the temperature at Birnunesborgir has varied but is approximately 74.7°C, and at Hamar 64.3°C. The monitored water temperature at Hamar by HD is clearly not showing the temperature of the water from the boreholes themselves, but rather the mixture including the water from Birnunesborgir, which is more than 10°C warmer than the average temperature of water directly from the wells at Hamar. It would be of great value to continue with consistency in monitoring each system and each borehole to make it possible to detect if there are any changes in the system, either natural changes or due to production.

In Figure 8 the monthly averages of flow rate and monthly averages of water temperature at Birnunesborgir are shown from 1999 to 2011. During the first years the system provided geothermal water to Árskógssandur and Hauganes as well as the industries in the surroundings. In the year 2006 mixing some water from Birnunesborgir with the water from Hamar started, hence increasing the flow rate from Birnunesborgir. The flow rate at Birnunesborgir increased rapidly when households in Svarfadardalur, the valley to the south and west of Dalvík, were connected to the system in late 2007. The temperature increased when the new well, ÁRS-32, stared producing and there is also increased scattering in the figure which coincides with the initialization of utilizing the new well, which is deeper and warmer than the older one, ÁRS-29. These two wells are used interchangeably, i.e. ÁRS-29 is used during less demanding seasons while ÁRS-32 is rested, so the temperature depends on the utilization well at that time. It is though not possible to exclude that there are problems in the measuring device causing errors. Yearly averages of the water temperature showed gradual increase from 2001. These last years it is not possible to detect direct change of temperature in one well since the temperature measurements are shifting between the two wells without distinguishing between them.

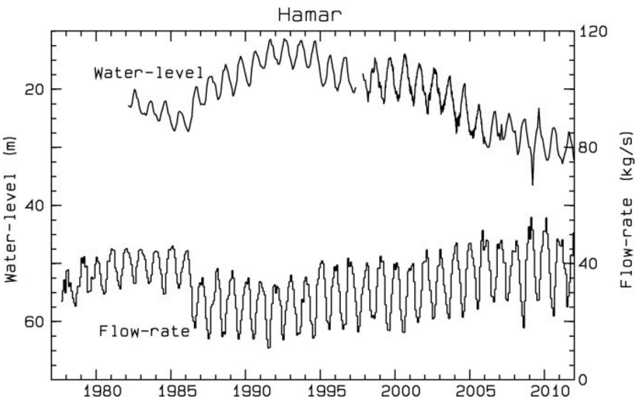

Figure 6. Hamar near Dalvík. Water-level and monthly averages of flow-rate from 1977 to 2011. (Adapted from Haraldsdóttir and Hardardóttir, 2012.)

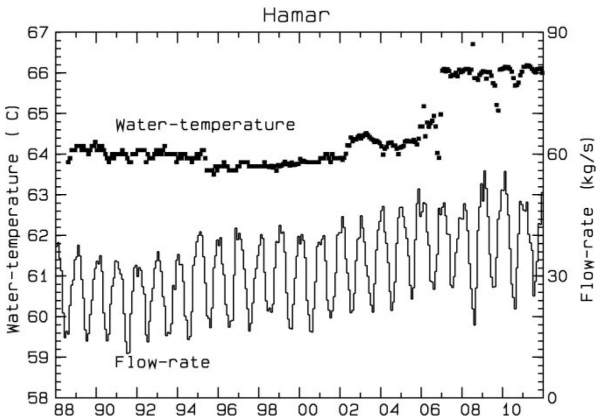

Figure 7. Hamar. Water temperature and monthly averages of flow-rate from 1988 to 2011. (Adapted from Haraldsdóttir and Hardardóttir, 2012.)

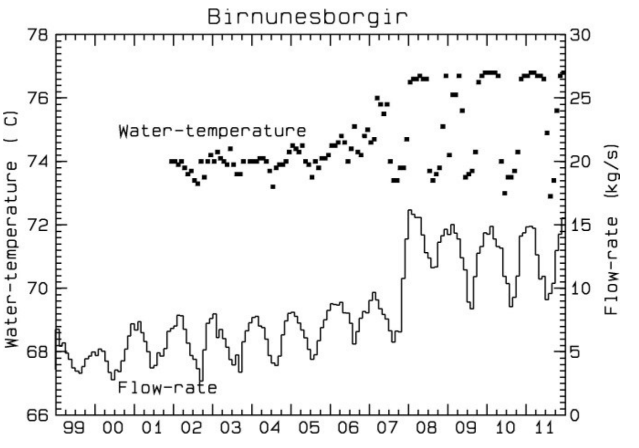

Figure 8. Birnunesborgir. Water temperature and monthly averages of flow-rate from 1999 to 2011. (Adapted from Haraldsdóttir and Hardardóttir, 2012.)

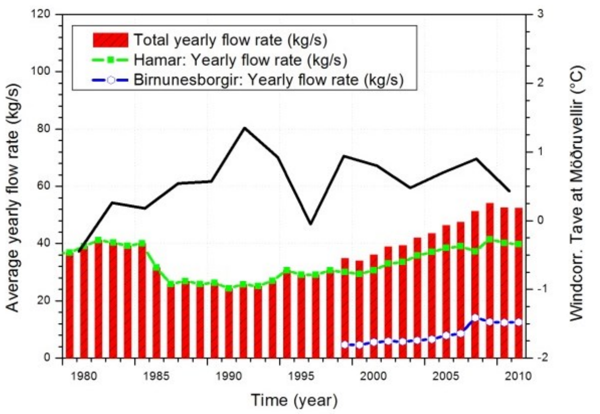

Figure 9. Yearly average flow rate at Hamar (green) and Birnunesborgir (blue) and the total flow rate (red poles), as well as yearly average temperature at Mödruvellir including the wind effect (black) from 1980 to 2011.

The total yearly flow rate (Figure 9) at Hamar, Birnunesborgir and the total system of HD, as well as the yearly averages of temperature including the wind effect at Mödruvellir do not seem to have a good correlation. The reduction in flow rate in 1986 is explained by the change in billing, when flow meters were installed in each household. From 2000 the geothermal water from Hamar to Dalvík was increasing gradually until 2007. There is an increase at Birnunesborgir in 2008 when Svarfadardalur was included in the distribution system. The lowering of flow rate that year at Hamar could be partly explained with the mixing with water from Birnunesborgir, utilizing less water but yet including relatively more energy due to the increased temperature. During the last two years 2010 and 2011, the yearly average total flow rate, as well as the yearly average for Hamar and Birnunesborgir individually, have reduced a little. The outdoors temperature is also lower, so there does not seem to be a direct connection of the flow rate and temperature. The explanations can probably rather be found in the changes in society during a recession, when people get more concerned about finances and the energy needs of industries and companies change with time e.g. with reduced heating of empty houses.

4. EGILSSTADIR AND FELL – GEOTHERMAL UTILIZATION

4.1 The geothermal system under and around Urridavatn

The municipal utility company, Hitaveita Egilsstada og Fella (HEF), provides geothermal water for heating and domestic use for 2900 inhabitants. Additionally there are two large summer cottage areas including 85 cottages which have access to the distribution system for the geothermal water.

Boreholes have been drilled under and close to the lake Urridavatn, since studies of surface manifestations indicated a fissure into the lake and temperature gradient wells showed an anomaly leading to the decisions of well locations (Figures 10 and 11).

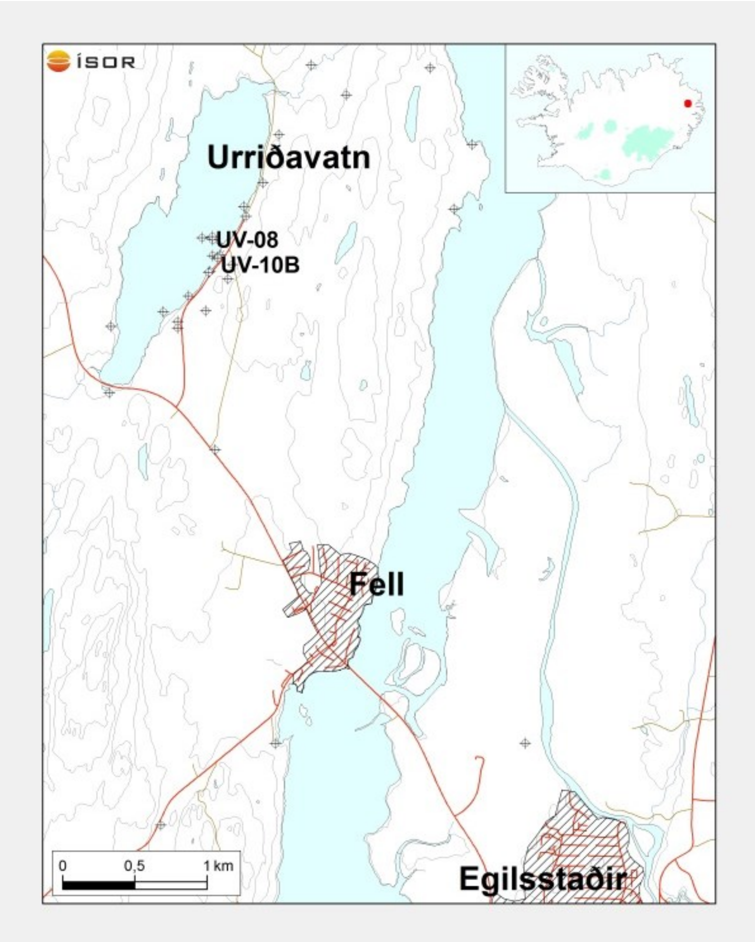

Figure 10. Egilsstadir, Fell and Urridavatn, East Iceland. The low temperature geothermal system at Urridavatn provides hot water for domestic use at Egilsstadir-Fell and the province in the vicinity. The figure also shows the main utilization wells in the field.

It had been common knowledge that there were holes in the ice (vakir) in lake Urridavatn (Jónsson, 1964), even during long periods of freezing (T< 0°C). The knowledge about a geothermal area was confirmed on 2 Jan. 1962 when temperature measurements showed 25°C at the bottom of the lake below one of the holes in the ice. Later during the same winter temperatures up to 59.5°C were measured in several places in the lake. Geological studies were initiated in the summer of 1963 in the vicinity of Urridavatn to find out if the geothermal system had a potential of providing geothermal water for heating and domestic use. The studies showed that tertiary basalts dominate the Urridavatn area as most of Austfirdir (the East fjords) in Iceland. Exploration wells were drilled and the fourth well which was drilled at Urridavatn was finally utilized in the beginning of the operation at the end of the year 1979 (Einarsson et al., 1983). The following year well number 5 was drilled and these two wells were the main utilization wells until 1984 (Figure 11). Their main feed zones were at a shallow depths and the water cooled within a year or two from 64°C to 53°C. The next well did not meet expectations so HEF was worried about the continuation of providing sufficient geothermal water to the users. This led to a review of available information at Orkustofunun and analysis to try to find out why the wells cooled so quickly and how to avoid it and how deep and where it could be possible to find warm and accessible feed zones, and a more stable system for utilization. Electromagnetic soundings and geological investigations were performed before continuing drilling wells.

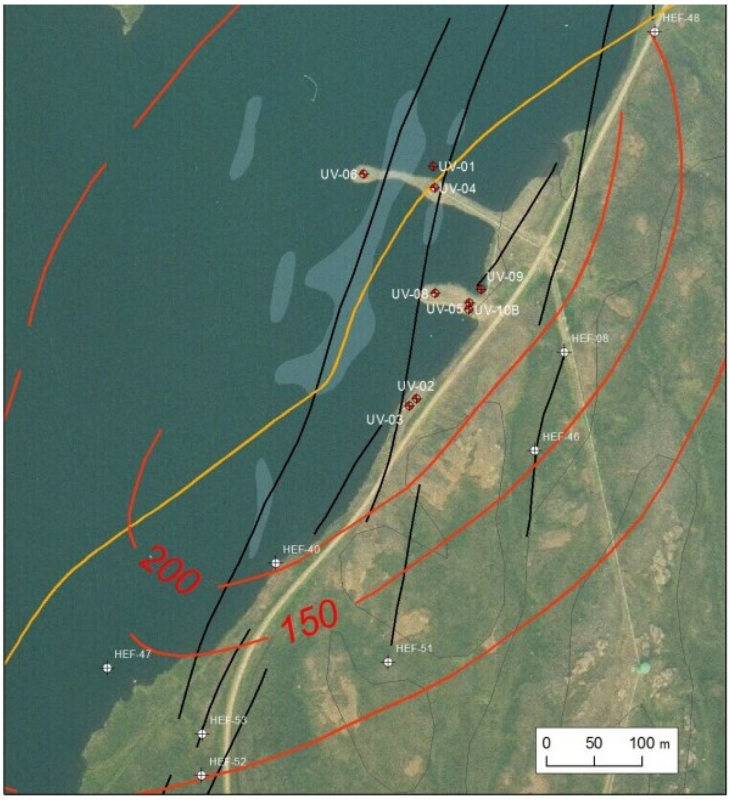

Figure 11. Urridavatn and holes in the ice (light gray shades), temperature gradient (red lines), low resistivity direction (yellow line), intrusions (black lines), UV-boreholes and other boreholes.

Geothermal gradient is very important for studying geothermal systems. In the map in Figure 11 the geothermal gradient has the highest values in the lake and the yellow line in the lake, represents the direction of the low resistivity, which has often been linked to temperature alteration minerals in the geothermal system. Dykes are shown in black and all of these are consistent in a NNE-SSW direction, which is the main tectonic direction in the area. The wells have been drilled in the lake, as UV-1, which was drilled from a platform on the lake, and from the shore of the lake, while the main geothermal system seems to be located under the lake.

At present a total of ten boreholes has been drilled of which two are mainly in operation but the third one can serve as a reserve. According to the old web of HEF (changed in May 2014) well UV-8 has the nick name Gold, UV-9 is a reserve well and well UV-10 is called the Diamond. UV-8 was the main well until late in the year 2006 when well UV-10B became the main utilization well. Well UV-9 had not been up to expectations and had only been used for extra power when needed. At present UV-10B is the main utilization well and UV-8 is used during maintenance or to rest the main well.

4.2 Utilization of the geothermal system under Urridavatn – data and results

The flow rate in UV-10B and the water level are shown in Figure 12. It may be noticed that there are periods of missing data in the flow rate series. This is partly when UV-8 was producing, and partly due to problems with the monitoring devices, e.g. 170 days in 2010, i.e. from the middle of February, parts of March and from 9 May to 16 September 2010 (Haraldsdóttir et al., 2011).

The upper diagram in Figure 13 shows daily averages of flow rate from the geothermal system under Urridavatn where well UV-8 was the main well until October 2006 after which well UV-10B has been the main well. The lower diagram shows daily averages of outdoors temperature including the wind effect. The utilization is calculated for approximately 170 days during 2010, i.e. from the middle of February, parts of March and from 9 May to 16 September 2010. In Figure 13 the correlation of flow rate and outdoors temperature seems rather good, and the flow rate including the calculated values where they were missing, which were calculated in a similar way to what we saw in the data from Hamar.

Figure 14 shows cross plots of flow rates against outdoors temperature where the wind effect has been added to it. The correlation varies a little between years. Figure 15 shows the selected known data from the year 2009 to 8 May 2010 on a cross plot in a similar way as in the previous figure, and the correlation was used to calculate the missing data. The selection includes more than a year of data to cover all seasons.

The water level in UV-10B (Figure 12) is missing during periods of maintenance or problems with the monitoring devices. From the limited data the water table seems to be relatively stable and in fact is higher during parts of 2009 than 2008. Probably the well has recovered after being rested for a while. This is far from enough of monitored data to say anything about the evolution of pressure in the well. It would be felt on the pumps if the water level reaches as far down as their depth. Monitoring is by all means best for being able to take actions based on knowledge.

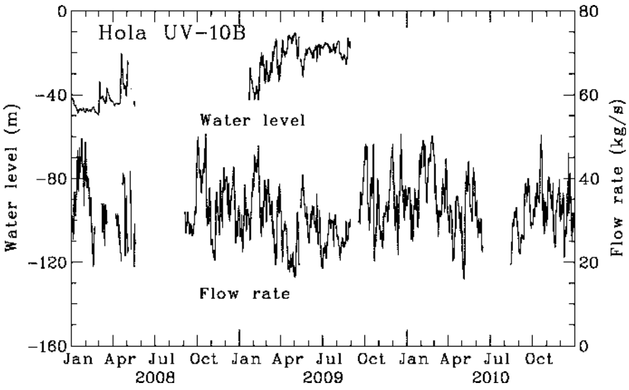

Figure 12. Daily averages of flow rates and water level in well UV-10B. Missing data represents days when the well was not utilized or there was an error in the data sampling. Flow rates were missing for 170 days in 2010. (Adapted from Haraldsdóttir et al., 2011.)

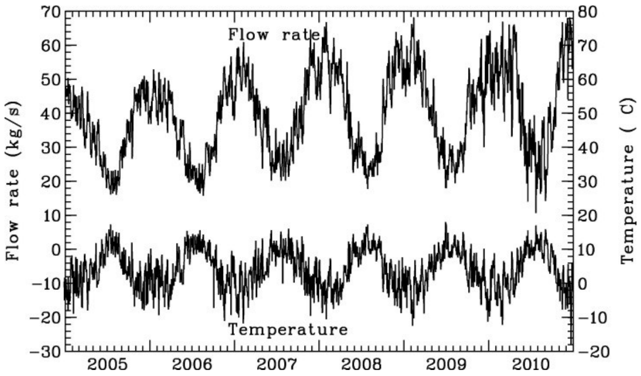

Figure 13. The upper diagram shows daily averages of flow rate from the geothermal system under Urridavatn where well UV-8 was the main well until October 2006 after which well UV-10B has been the main well. The lower diagram shows daily averages of outdoors temperature including the wind effect. (Adapted from Haraldsdóttir et al., 2011.)

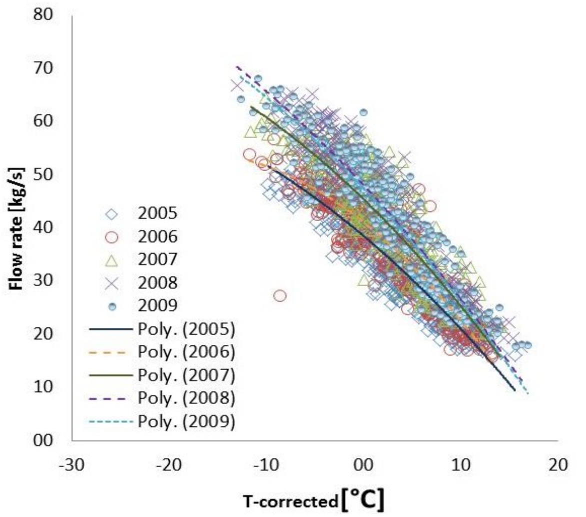

Figure 14. Daily averages of flow rates at Urridavatn as a function of daily temperatures, including the wind effect, for each year which can be used to fill in data and for short term forecast. (Adapted from Haraldsdóttir et al., 2011.)

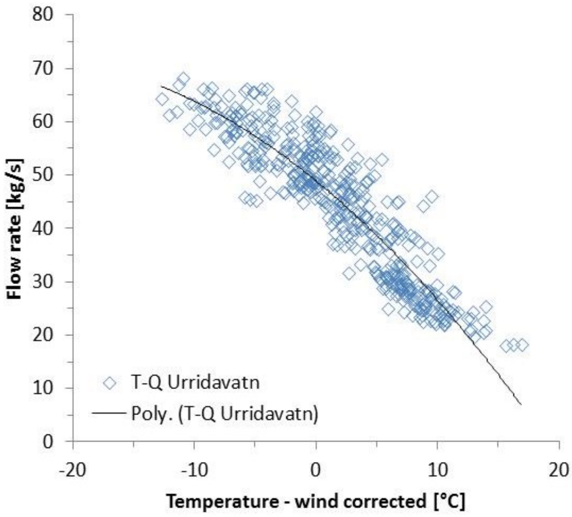

Figure 15. Daily averages of flow rates at Urridavatn and daily temperatures, including the wind effect, 2009 to 8 May 2010. Flow rate data was missing for 170 days in 2010, hence using data from 2009 and part of 2010 to account for all of the seasons. (Adapted from Haraldsdóttir et al., 2011.)

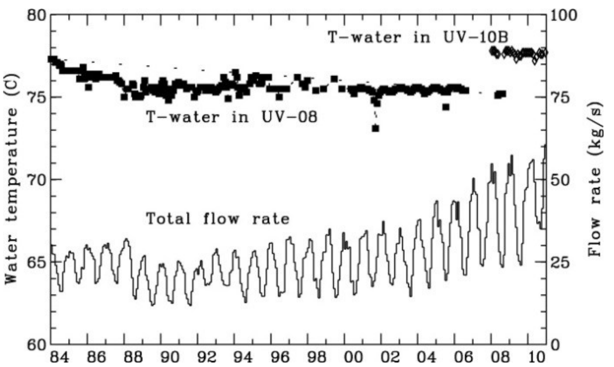

Figure 16. Monthly averages of total flow rate and the water temperature from well UV-8 throughout its production history and UV-10B from 2008 (diamonds in the upper right corner). (Adapted from Haraldsdóttir et al., 2011.)

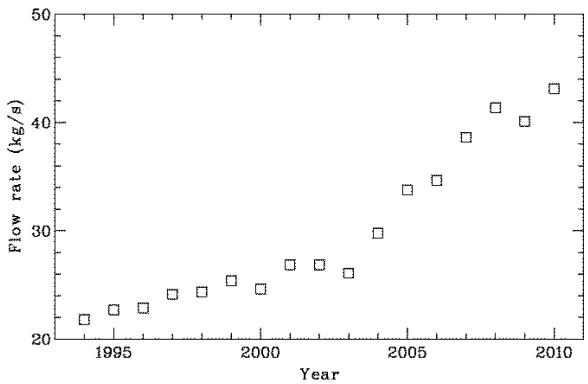

Figure 17. The yearly averages in (kg/s) from the geothermal system under Urridavatn 1994–2010. (Adapted from Haraldsdóttir et al., 2011.)

Figure 16 shows the monthly averages of flow rate from UV-8 and UV-10B and the water temperature in the wells during their relevant periods of production. The rise in temperature is when the operation of UV-10B started in 2008. The temperature of the water from UV-8 had gradually reduced while it was still the main well in the Urridavatn system and was 75.5°C at the end of that period. In 2008 it was 75.2°C when the well was producing for a while, probably caused by mixing with colder water. This was confirmed when less minerals were found in water samples during the resting periods of UV-8 after it became a reserve well and was sitting for months. The temperature in UV-10B has been stable from the beginning of monitoring or from 2008 to 2010, 77.7°C. The temperature measurements indicate that the system is stable with respect to temperature which is especially positive when you bear in mind the problems with wells 4 and 5 in the beginning of operation of HEF. Still it is not possible to know if the system is utilized in a sufficiently good way for future production, but better monitoring would help. The water table needs to be monitored to be able to see if the pressure is stabilizing, i.e. the water table is in balance.

In the years 1994 to 2004 Heitaveita Egilsstada og Fella needed more warm water than the geothermal wells provided so a diesel station was used to warm up cold water to use with the geothermal water for satisfying the domestic needs. After UV-10B became the main well, the flow rate from the geothermal system has been sufficient for the needs of the communities and the temperature of the water has not changed from 2008. Yet it is clearly necessary to keep monitoring in a more stable way to be able to manage the system and in case of changes, avoid a severe situation later. It can be seen in Figure 17 that the utilization has been increasing with time, except in 2000, 2003 and 2009. The changes in utilization may sometimes be explained partly by changes in weather but mainly by evolution of the society, providing geothermal water to an increasing number of homes and industries. The reduction between 2008 and 2009 may be due to the recession in Iceland, possibly reducing the warming of empty houses which had been built due to optimism in this area during the years before the collapse.

5. CONCLUSIONS AND RECOMMENDATIONS

The conditions for geothermal utilization with respect to energy source, water and permeability seem to be met in the geothermal systems utilized by both of the utility companies in this study. In the two systems near Dalvík and the one in Urridavatn the main tectonic direction is NNE-SSW, and Dalvík is located within a major earthquake zone. Boreholes were aimed at fractures or dykes and even better where they intersect. Monitoring has been relatively good with long series of data.

The water level at Birnunesborgir is not available and temperature monitoring at Hamar has during recent years been of a mixture of water from Hamar and Birnunesborgir, hence not showing the evolution of one system individually, which is necessary. Monitoring continuously can never be overestimated both for following the obvious evolution of the system and for modeling the system using data from the monitoring thereby finding their modeled limits for sustainable utilization and the time of a possible cold front to enter the system.

Hamar was studied previously with a lumped model giving approximately 40 kg/s as a limit of sustainable utilization (Axelsson et al., 2005, Axelsson, 2010) for 200 years or more. In 2011 the production was at this limit, but with water from Birnunesborgir mixed with the water from Hamar during recent years, thereby increasing both the flow rate and the temperature. The problem is though that the monitoring does not show a continuous series of similar data after the mixing, due to the fact that the monitoring was partly measuring the mixture, not only Hamar. To model a system it is much better to have information about each system individually. The geothermal system at Birnunesborgir needs to be modeled to try to see its limits with the present wells. It is necessary to monitor the water table and keep monitoring the production and temperature of the wells, preferably individually.

This year Hitaveita Dalvíkur will be the first central heating company in Iceland to finish a modification in equipment so the billing will be based on energy, or kWh, instead of volume of water according to the head of the utility company, HD.

The available flow rate data from Hitaveita Egilsstada og Fella for Urridavatn reach back to 1980. As for Hitaveita Dalvíkur, the flow rates are partly deduced from the relation to outdoors temperature at the site for periods of missing data. When the utilization started two wells were used but their temperature reduced rapidly. After research more wells were gradually drilled and from 2009 the main well in production has been UV-10B, and UV-8 is a reserve well, which for many years was the main production well. The water from UV-10B is warmer than from UV-8 and, over 77°C and 75°C respectively. The available water level measurements from UV-10B show that it was around 40 m depth, but rises to 15 to 20 m depth after the well is rested. The production has increased during the last years but information about the water table is not available except during short periods of time. It is necessary to monitor the water table continuously to avoid overexploitation and be ready with solutions in case of severe draw down or a cold front arriving, which could be found with models, but data is necessary for robust modelling.

The nature of geothermal space heating generally involves that the energy demand increases with time where the population is increasing or some industries are started. Therefore it is not enough to look only at the present production, it may be necessary to try to forecast the possible production scenarios for a system, and plan ahead for evolution in the society, and to explore more thoroughly the relevant geothermal system. In some cases it may be necessary to find new solutions, such as reinjection, new boreholes and possibly use other geothermal systems.

The management of the geothermal central distribution for the village, Dalvík, was indeed to supplement from another geothermal system. The water at Hamar was not sufficient with increasing demand and was therefore mixed with water from Birnunesborgir, which was warmer. As was seen in the paper the temperature increased by approximately 2°C by mixing with some of the 75°C warm water from Birnunesborgir whereas the water at Hamar was at 64°C prior to the mixing.

In both parts of Iceland which were studied the systems seem to be managed relatively well, adding wells to the utilization system when needed, but there is a lack in the monitoring and in modelling the systems. It may be much less expensive to do better monitoring of each well than suddenly face overexploitation, somewhat less water available than expected or colder water.

The value of regular monitoring cannot be overestimated to be able to follow the evolution in the system and take actions if necessary before severe problems occur. Monitoring of water level, flow rate and temperature of each well gives key data necessary for modelling in order to optimally manage the wells and utilization system for both effectiveness and sustainability.

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