

Dealing with intense production density: Challenges in understanding and operating the Hellisheiði Geothermal Field, SW-Iceland

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ABSTRACT

The Hellisheiði Power Plant is located in the southwestern part of the Hengill Area, SW-Iceland, 25 km SW of Reykjavík. The Hengill Area consists of the Hengill Central Volcano and fracture zones northeast and southwest of Mt. Hengill. The Hellisheiði Power Plant was commissioned in 2006, and expanded in 2008 and again in 2011. The current installed capacity is 303 MW electric and 133 MW thermal. Another power plant, Nesjavellir, is located in the northeastern part of the Hengill Area. That plant was commissioned in 1990 and has an installed capacity of 120 MW electric and 290 MW thermal.

Original conceptual models of the geothermal fields in the Hengill Area postulated an up-flow zone under Mt. Hengill in the center of the area. That up-flow was assumed to be the power source of both the Hellisheiði and the Nesjavellir fields as well as of other fields in the area. This one up-flow hypotheses worked reasonably well for operating the Nesjavellir field and simulating the geothermal reservoir there.

The development plans for the Hellisheiði Power Plant relied on the original conceptual model. However, down-hole data from wells drilled in the southwestern part of the Hengill Area during the development of the field brought the soundness of the one up-flow hypothesis into question. The formation temperature of in the area is characterized by localized temperature maxima separated by cooler regions and the hotter parts of the system are much smaller than assumed when the Hellisheiði Project was planned. Due to the fast pace development of Hellisheiði it was not possible to adapt to this new reality. As a result the Power-Plant built was too big for the current production field.

Operating the Hellisheiði Power Plant near full capacity has been a challenge due to the intense production density. The production density is approximately 250 kg/s/km² (or 40 MW/km² in electricity) within the most productive parts of the field. This high production density has caused significant pressure drawdown and decreased performance of wells. Reinjection has been used for maintaining the reservoir pressure, mainly on the edge of the production field. Experiments have also been done with in-field reinjection. Another approach to solve the operational problems has been to expand the production field, i.e. to find another resource. A promising field is known in Hverahlíð in the southern part of the Hengill Area, approximately 5 km from the Hellisheiði Power Plant. Wells there were recently connected to the Hellisheiði Power Plant.

As mentioned above the down-hole data from the wells drilled during the development of the Hellisheiði field contradicted previous conceptual models of the Hengill Area. As a result the conceptual model needed to be revised and numerical reservoir models had to be updated. This has also opened questions on the origin of the geothermal activity in volcanic system as the Hengill Area.

1. INTRODUCTION

The Hellisheiði Geothermal Field is located in the SW part of the Hengill Area, 25 km SW of Reykjavík. The Hengill Area consists of the Hengill Central Volcano and fracture zones northeast and southwest of Mt. Hengill. Hot springs and fumaroles are widely found in the area. Due to close proximity to Reykjavík, the geothermal fields of the Hengill Area are considered important energy resources, both for electricity and space heating. Three Holocene eruptions are known in the Hengill system, 2000, 5800, and 10'000 years ago. The eruption fissures of these eruptions were located on the fissure swarm both north and south of the higher central part of the Hengill Volcano, but not in the central part (Sæmundsson 1967, 1992, 1995).

The Hellisheiði Power Plant was commissioned in 2006, expanded in 2008, and again in 2011. It produces from the fissure swarm area south of the Hengill Mountain (see map in Fig.1). The current installed capacity is 303 MW electric and 133 MW thermal. The average enthalpy of produced fluid was originally ~1800 kJ/kg but has been decreasing and is now ~1600 kJ/kg. The power plant uses a double-flash steam cycle for electricity generation. A schematic of the power plant is shown in Fig.2. The electricity is generated in six high pressure units and one low pressure unit. The separated water is then used to heat up fresh ground water in heat exchangers in the district heating utility of the power plant. The heated ground water is pumped to the Reykjavík Area where it is used for space heating and the cooled separated water is reinjected into the reservoir. Another power plant, Nesjavellir, is located in the northeastern part of the Hengill Area. That plant was commissioned in 1990 and has installed capacity of 120 MW electric and 290 MW thermal.

The most productive part of the Hellisheiði field is narrow resulting in high production density. Thus, reinjection is essential for maintaining reservoir pressure. Reinjecting the separated water is, however, not a trivial task. Drilling reinjection wells with enough

capacity and maintaining that capacity has been a challenge. Due to the fracture dominated behavior of the permeability of the reservoir,

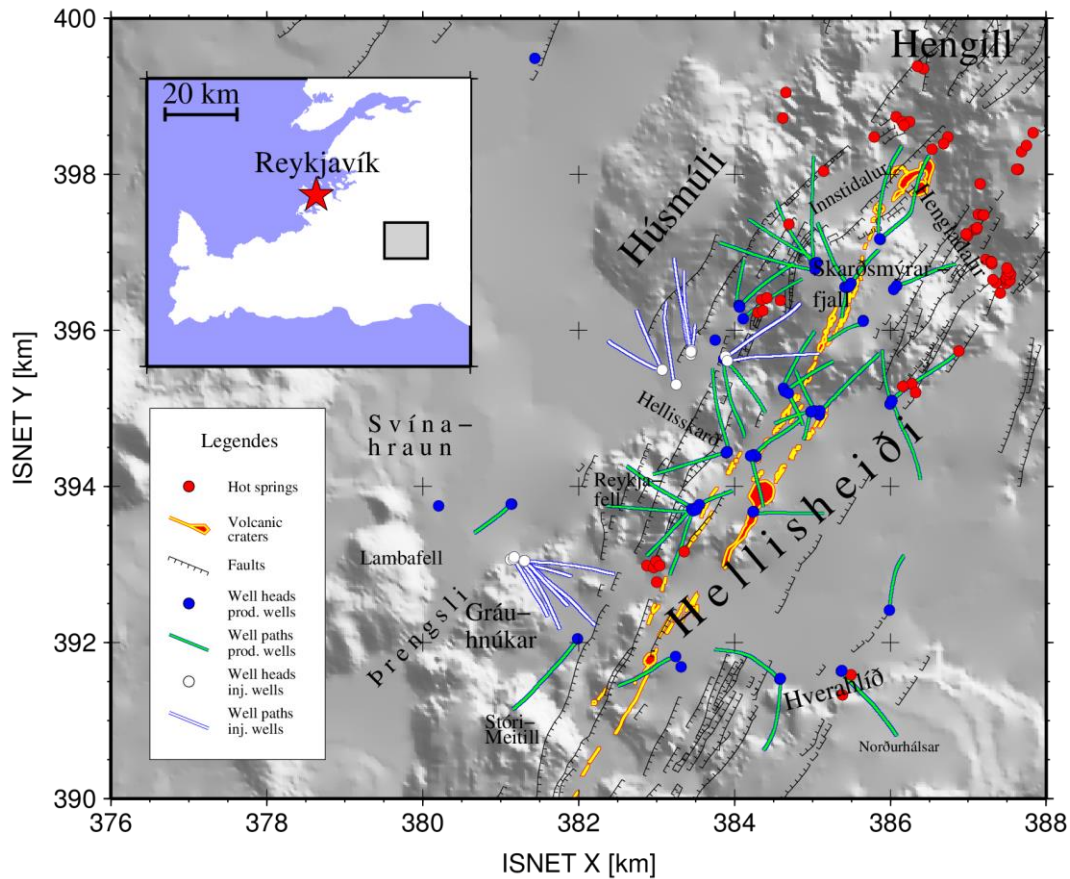


Figure 1: A map of the Hellisheiði Geothermal Field, SW-Iceland. The inset shows the location of the field in SW-Iceland. The main production field is located on the fissure swarm west of the eruption fissure and north of the Gráuhnúkar Reinjection Zone. A new production field is now being developed in Hverahlíð in the south of the Area.

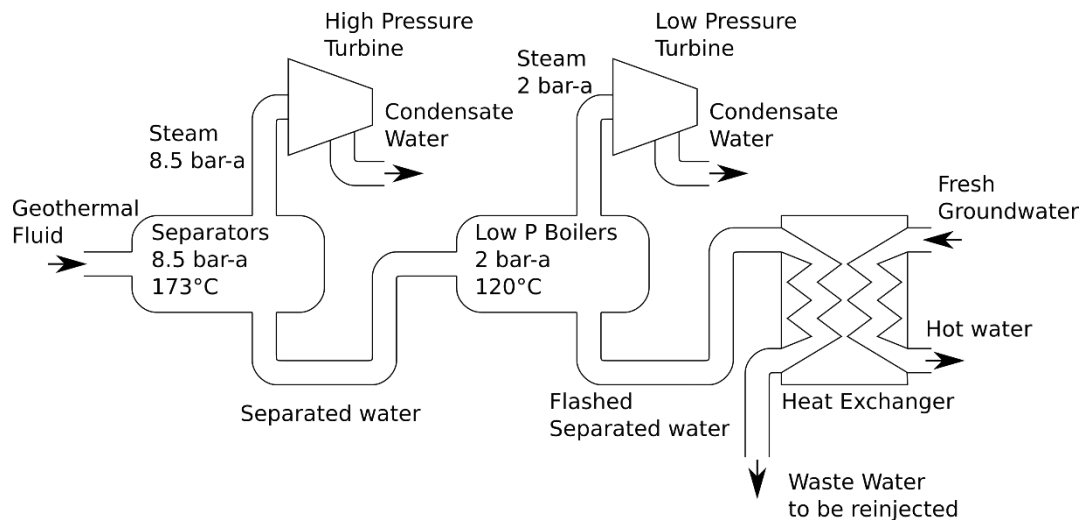


Figure 2: The Hellisheiði Power Plant in a nutshell. A double flash system is used for electricity generation. The flashed separated water is then used to produce hot water for direct use (space heating).

cooling the injected fluid increases the permeability of the reinjection wells. By operating the heat exchangers of the district heating utility at maximum capacity and by cooling the separated water further by mixing it with condensate water, it has been possible to reinject all the separated water back into the reservoir (Gunnarsson 2011, 2013). Thinning the separated water with condensate water does also mitigate the risk of silica scaling in the wells.

The effects of reinjection on the production properties of the Hellisheiði field are of concern. Huge quantities of water are reinjected in the vicinity of important production wells. Preliminary results from tracer tests indicate that thermal break-through could occur in parts of the system. These results and the fact that the production field is narrow show that it is necessary to find additional resources if the production capacity of the power plant is to be maintained

2. CONCEPTUAL MODELS AND THE DEVELOPMENT OF THE HELLISHEIÐI POWER PLANT.

Original conceptual models of the geothermal fields in the Hengill Area postulated an up-flow under Mt. Hengill in the center of the Area. That up-flow was assumed to be the power source of both the Hellisheiði and the Nesjavellir fields, as well as of other fields in the Area. This one up-flow hypotheses worked reasonably well for operating the Nesjavellir field and simulating the geothermal reservoir there (Franzson et al. (2005), Björnsson et al. 2006). However, when the Hellisheiði Field was developed in the early 2000's, down-hole data from wells in the southern part of the Hengill Area became available. Formation temperature estimates in these wells and also in new wells drilled elsewhere in the Hengill Area, brought the soundness of the one up-flow hypothesis into question. In Fig.3 the estimated formation temperature at a 1000 m below sea level in the southern part of the Hengill Area is shown. As can be seen the formation temperature is characterized by narrow structures. Narrow hotter zones are surrounded by cooler areas. The formation temperature does not increase towards the assumed center of the up-flow north of the Hellisheiði field. On the contrary, the highest temperatures are found in the center of the field and in a separate high temperature anomaly in Hverahlíð in the southernmost part of the area. This contradicts the single up-flow hypothesis. These sharp structures in the formation temperature can be explained by shallow heat sources that are driving the geothermal systems in the area. Local anomalies in permeability could also explain them.

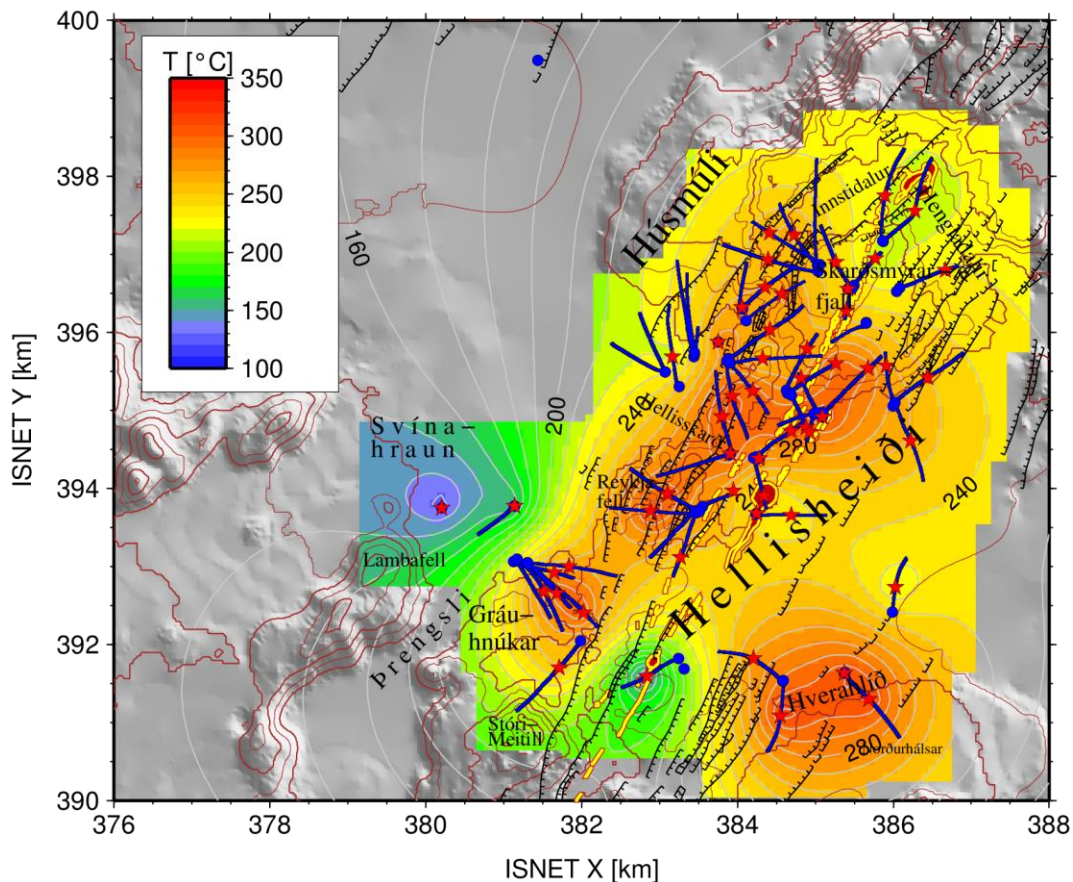


Figure 3: Formation temperature in the Hellisheiði Area at the depth of 1000 m below sea level. Red stars show data points (where wells intersect 1000-m below sea level). The temperature in between is interpolated using the surface interpolation scheme of the GMT software package (Wessel & Smith, 1998).

Recent modelling work of the Hengill Area is based on a conceptual model that postulates smaller local heat sources as energy sources of the geothermal fields in the area (Gunnarsson et al., 2011a). This conceptual model has worked reasonably well to reproduce the formation temperature and the newest version of the model works well in reproducing the pressure draw-down as it is measured in monitoring wells in both production fields in the area.

This finding that the geothermal fields in the Hengill area are characterized by narrow hot areas with cooler regions in between does not only affect our understanding of the geothermal systems in the area and geothermal systems in the rift zones of Iceland in general. It has also had considerable practical consequences. The development of the Hellisheiði Power Plant was undertaken in a very fast pace. All decisions on the size of the Hellisheiði project were taken before comprehensive analysis of the data from new wells in the southern part of the Hengill Area became available. Those decisions were therefore based on the older single up-flow hypothesis. Thus, the most productive part of the system is much narrower than expected at the time of these decisions.

3. PRODUCTION DENSITY AND RESERVOIR RESPONSE

The most productive part of the field proved to be a relatively narrow strip along the fissure swarm west of the eruption fissure between the Gráuhnúkar reinjection zone and south of Skarðsmýrarfjall. This strip is about 1 km wide and 4 km long and it coincides with the highest formation temperature within the production field as can be seen in Fig.3. Very productive wells are also in the NW part of the drilling field, but their enthalpy is much lower than for the wells in the center of the field. The total installed capacity of the power plant is 303 MW_e and therefore the production density in the most productive part of the field is extremely high. The production density is shown in Fig.4 where the total mass production in kg/s/km² is shown as it was on the average in year 2015. The maximum production density is > 200 kg/s/km² in the center of the field. The average enthalpy of the produced fluid is 1600 kJ/kg, which means that the steam ratio at separation pressure is ~43%. Approximately 2 kg/s of steam is required to produce 1 MW of electricity. Thus, the electric power density of the production is ~42 MW_e/km². In a closed system such a high production density would result in an annual drawdown of ~80 m or ~6 bar (assuming average temperature of 275°C).

The measured pressure draw-down in the system is however lower than this. The drawdown measured in wells in the production field is shown in Fig.5. The average annual drawdown is 3.5-4.2 bar, which is lower than for a closed system, due to reinjection and natural recharge. However, this drawdown has had considerable effects on the production properties of the geothermal field. In Fig.6 the annual production of the field is shown. The last expansion of the power production took place in autumn 2011 and the production peaked in 2013. Since then the production has been decreasing. The flow from most of the wells has been declining, especially from the most powerful ones. The average enthalpy of the produced fluid has also been decreasing. Initially it was around 1800 kJ/kg but is now around 1600 kJ/kg.

Solving this problem of declining production capacity has been a challenge. This has been done by reinjecting waste water into the reservoir. New methods have been tested in reinjection such as in-field reinjection, where unproductive production wells have been converted into injection wells. The amount of injected water which has grown from year to year can be seen in Fig.6. Last year almost 80% of the produced fluid was reinjected into the reservoir. The rest evaporates in cooling towers or is condensed water, which is injected into shallow wells. Reinjection is however not sufficient to maintain the production capacity of the Hellisheiði Field. Another approach to deal with declining productivity has been to expand the production field. Due to high production density, drilling make-up wells within the same production area is not a sustainable way of maintaining the production capacity. New resources have to be found to spread the production if it is to be maintained at present level.

4. MAINTAINING THE PRODUCTION CAPACITY

4.1 Reinjection

Reinjection has been used for maintaining the reservoir pressure, mainly on the edge of the production field. Two reinjection zones are operated at the Hellisheiði Power Plant; Gráuhnúkar in the southern part of the area and Húsmúli on the western edge of the field. The Gráuhnúkar area is the original reinjection zone of the Power Plant. During drilling, high temperatures (> 300°C) were measured in wells there. Due to these high temperatures, it has been considered a feasible option to convert the Gráuhnúkar area into a production zone. The other reinjection zone; Húsmúli, was planned in order to replace the Gráuhnúkar zone. The capacity of the reinjection wells in Húsmúli is, however, not high enough to be able to stop reinjecting in Gráuhnúkar.

Experiments have also been done with in-field reinjection. Two unproductive production wells near the center of the field (HE-13 and HE-40) were converted into reinjection wells. The location of the wells is shown in the inset of Fig.5. The capacity of those wells proved to be very high. The permeabilities of the wells' feed zones seems to increase significantly when water, which is cold compared to the formation temperature, is pumped into them. The formation temperature in the wells is around 300°C near the bottom and the reinjection water has a temperature in the range of 55-120°C, normally around 60°C. The effects of cold injection on the permeability of wells is well documented in the Hellisheiði Field (Gunnarsson, 2011b, 2013).

In order to estimate the risk of thermal break through due from injection wells to production wells, tracer tests were undertaken. Tracers were injected into the reinjection zones in Gráuhnúkar and Húsmúli and into the in-field reinjection wells. Recovery was very high in the northernmost part of the field, where water from the Húsmúli reinjection zone was recovered. Cooling has, however, not been measured in wells there, even though simple modeling, based on the tracer tests indicate that thermal break-through should already have happened. The recovery was not as high from the Gráuhnúkar reinjection zone and the in-field reinjection wells. The risk of thermal break-through is therefore considered to be low. The performance of the wells in the vicinity of the Gráuhnúkar Reinjection Zone also seems to be supported by the reinjection. The wells in the vicinity of the in-field reinjection have, however, been changing rapidly after

the reinjection started. The enthalpy of produced fluid decreased even though tracer tests indicate that the risk of thermal break-through is small.

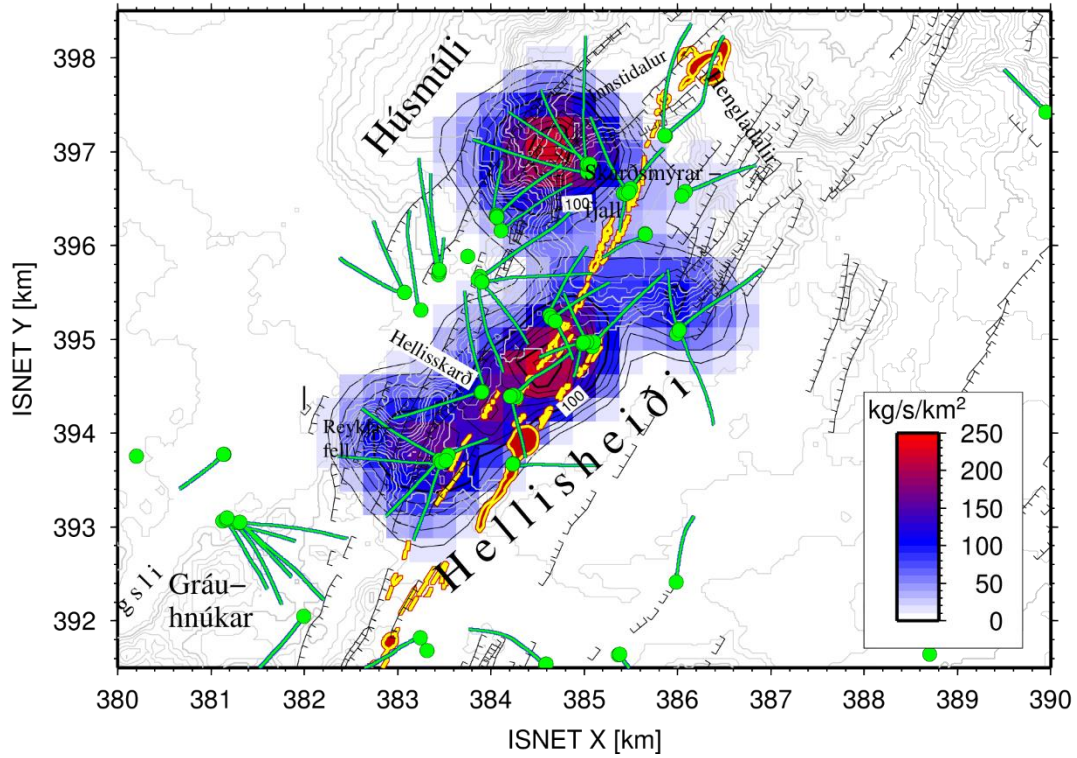


Figure 4: The production density in the Hellisheiði field. The average production of each well in the year 2015 was used to calculate the total mass extraction per area.

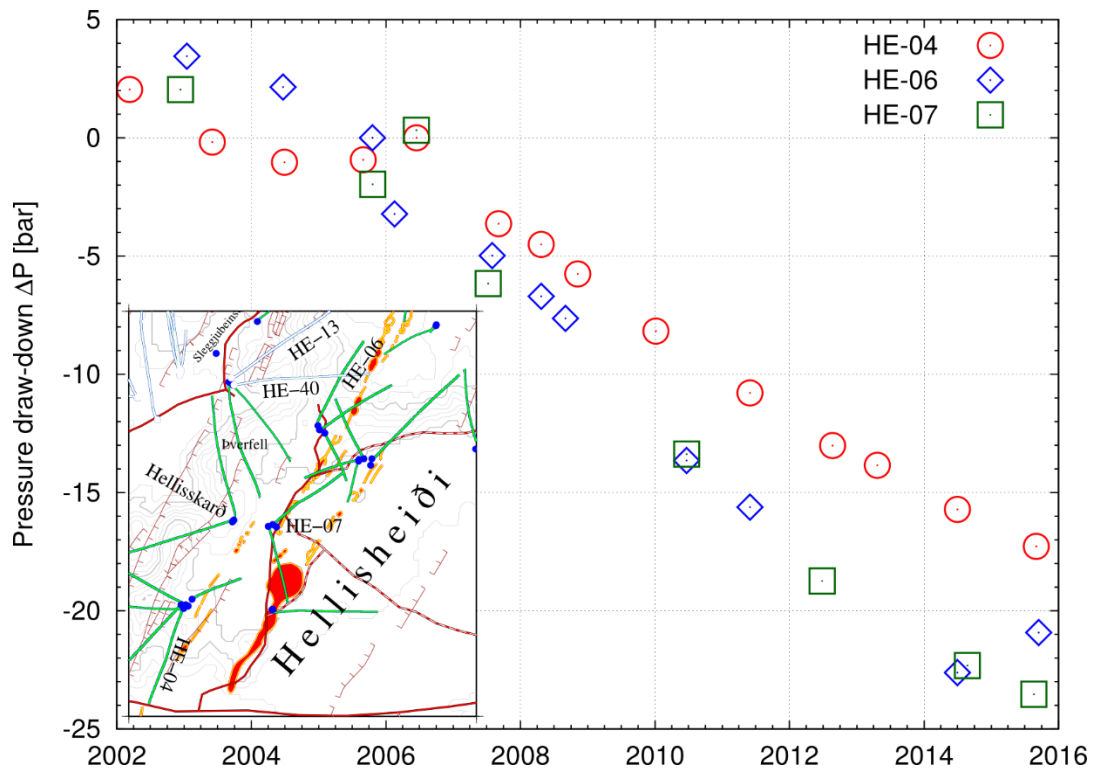


Figure 5: Pressure drawdown in three wells, HE-04, HE-06, and HE-07, in the Hellisheiði field. The inset show the location of these wells and the in-field injection wells; HE-13 and HE-40.

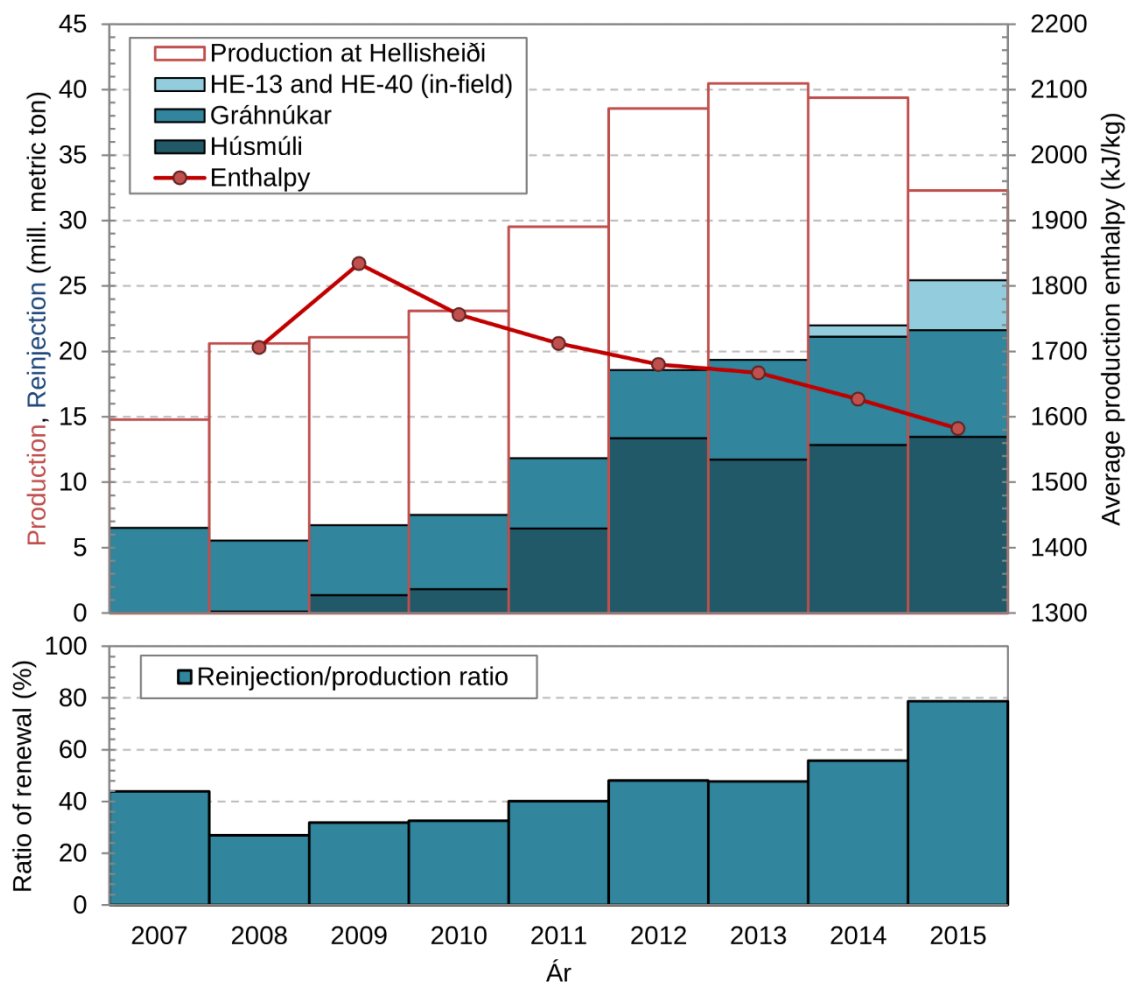


Figure 6: The annual total production and injection at the Hellisheiði Field. The lower graph shows the ratio of injection to the total production, the ratio of renewal.

The enthalpy of wells near the in-field reinjection wells has, as mentioned above, decreased rapidly since the reinjection there started. Due to operational problems during the summer and fall of year 2015 the reinjected water was not cooled properly. That resulted in lower capacity of the Húsmúli and Gráuhnúkar reinjection zones and therefore much more water than recommended was reinjected into the in-field reinjection wells. Recommended maximal flow under normal operations was 25 kg/s in each well. It was considered safe to inject 50 kg/s into each wells for shorter periods in case of operational problems. The total flow into the wells during the summer of 2015 was sometimes more than 250 kg/s. A closer look into the pressure draw-down in Fig.5 reveals the effects of the in-field reinjection on the pressure of well HE-06 and possibly HE-07. The pressure rises between the year 2014 and 2015 in well HE-06 and the drawdown seem to slow down in well HE-07. The fluid from the wells in the vicinity of the in-field is of medium to high enthalpy (1500-2500~kJ/kg). The reservoir in its initial state was water dominated. Higher enthalpies are due to boiling in the formation due to pressure drop. Raising the pressure suddenly in the reservoir could slow down this boiling and even stop it, which would result in lower enthalpy of the produced fluid.

4.2 New resources

Another approach to solve the operational problems has been to expand the production field, i.e. to find another resources. As mentioned above it has been proposed to convert the Gráuhnúkar reinjection zone into production zone, because of high temperature measured in wells there. It has, however, not been possible to find enough injection capacity for the water that is presently injected in the Gráuhnúkar reinjection zone and according to operational permit of the Power Plant it is required that all separated water is to be reinjected into the reservoir. Thus, the reinjection capacity of the power plant has to be increased if any experiments to convert the Gráuhnúkar reinjection zone to a production field are to be undertaken. Moreover, it is not clear how the long term injection has

affected the production capacity of the Gráuhnúkar Area. Waste water has been reinjected into wells there since 2007 and the total amount of injected water is 57.6 million metric tons.

Another promising production field is within reach for spreading the production over a larger area. That field lies in Hverahlíð in the southern part of the Hengill Area, approximately 5 km from the Hellisheiði Power Plant. Wells there were recently connected to the Hellisheiði Power Plant. The Hverahlíð field was originally planned as a separate project with its own power plant. The high power density and resulting decline of the production capacity of the Hellisheiði field has led to the total reconsidering of the operation in the southern part of the Hengill Area. It is now considered a better solution to operate the Hellisheiði and Hverahlíð Field together and bring all the geothermal fluid to the Hellisheiði Power Plant. Operating both fields as a one field offers much more flexibility in adapting the production to changes in the production properties of the geothermal fields.

The Hverahlíð field is not fully explored. The northern and the western edges of the temperature anomalies there are well known. The eastern and the southern edges are, on the other hand, are not known. Further exploration drilling is required to find the distribution of the temperature anomaly to the east and to the south. The best possibility of enlarging the Hellisheiði-Hverahlíð Field further is likely to be found in Hverahlíð. It is not clear if the resources that can be found in Hverahlíð are big enough to increase the installed capacity of the Hellisheiði Power Plant. As of now it is more likely that the resources in Hverahlíð will be used to maintain the existing production capacity of the Hellisheið Power Plant.

5. UNDERSTANDING THE HELLISHEIÐI FIELD

The distribution of formation temperature that was unveiled during the development of the Hellisheiði Power Plant showed that older conceptual models can no longer be applied. These older conceptual models postulate an up-flow of hot fluid under the highest part of Mt. Hengill north of the Hellisheiði Field. That hot up-flow is supposed to drive the geothermal field in the entire Hengill Area. Heat sources are supposed to be at the depth of a few kilometers and the heat is transferred by a supercritical convection to the conventional geothermal system above. Between these systems should be a low permeability barrier (Björnsson et al 2006, Franzson et al. 2005). This is shown schematically in Fig.7

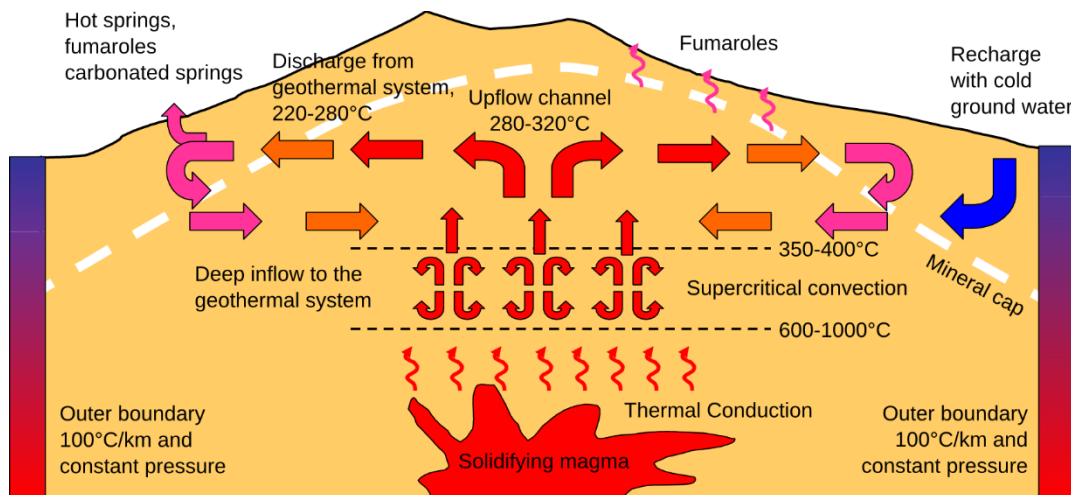


Figure 7: Older conceptual model of the geothermal systems in the Hengill Area and if geothermal systems in the volcanic active zones in Iceland in general. (Adapted from Andrésdóttir (2005)).

The sharp forms in the formation temperature as can be seen in Fig.3 contradict this conceptual model. They can be explained by local heat sources at shallower depths (2-3 km). It is not only the formation temperature that contradicts this model. There are strong indications that the heat sources of the geothermal systems in the volcanic active zone of Iceland are at much shallower depths than previously believed. There are two well documented examples of wells being drilled into the heat sources. At Nesjavellir a very hot formation was drilled into at the depth of 1800 m in 1985 (Steingrímsson et al. (1990)) and in Krafla, N-Iceland, a well was drilled into magma at the depth of 2.1 km. (Friðleifsson et al. (2010)). Moreover, calculations have shown that shallow heat sources in the form of dykes within the geothermal system itself are sufficient energy source to create and maintain a geothermal system of similar size and shape as can be found in the Hengill Area (Gunnarsson & Aradóttir, (2015)).

Understanding the nature of the geothermal systems is essential for operating production from them properly. Conceptual models of the geothermal fields have to be consistent with their observable properties. A new project with the aim of revising the conceptual models of the geothermal fields in the entire Hengill Area was recently started. This work will coincide with revision work done on the numerical model used for managing the production in the Hengill Area. A better understanding on the nature of the geothermal systems will be very useful in dealing with the operational issues of the Hellisheiði Power Plant and it is also key in finding new methods in maintaining the production capacity of the geothermal field.

6. CONCLUSION AND SUMMARY

The development of the production field in Hellisheiði was undertaken at a very fast pace. Decisions were consequently often based on limited information on the geothermal system in the actual drilling field. An existing conceptual model of the Hengill Area was used for decision making on the size of the project. However, when data analysis from new wells drilled during the development phase became available, the geothermal system looked very different from what was initially assumed. Instead of having one big geothermal system in the entire Hengill Area driven by a single up-flow of hot fluid under the highest part of the Hengill Volcano, there are a few separated relatively narrow hot zones separated by cooler regions.

The highest formation temperatures in the Hellisheiði Field can be found in a relatively small area (see Fig.3). The wells drilled there are the most productive ones. Wells drilled in the NW part of the field are also productive in terms of total mass flow but their enthalpies are much lower than in the center of the field. As mentioned above decisions on the size of the power plant were taken before down-hole data became available from wells in the Hellisheiði field. Thus, the installed capacity of the power plant is larger than might have been the case if accurate information on the size of the geothermal system had been available. The production in the Hellisheiði Field is concentrated in a narrow zone and the resulting production density is very high (see Fig.4).

Managing production in the Hellisheiði Field will be a challenge due to the high production rate per area. This high production density has affected the production properties of the field. The flow from the wells has decreased rapidly since the power plant reached final size in autumn of 2011. Reinjection has been used for maintaining the reservoir pressure. Two reinjection zones; Gráuhnúkar and Húsmuli are operated on the edge of the production field and experiments have been done with in-field injection. The effects of the reinjection is not fully understood. There have been no direct signs of thermal breakthroughs between reinjection and production wells. There are however, indications that higher reservoir pressure due to in-field reinjection could lower the enthalpy of wells in the vicinity. The pressure draw-down due to production causes water to boil in the formations if temperature is at boiling curve. Rising pressure would eventually stop that boiling which would result in lower enthalpy of produced fluid.

It is clear that reinjection alone is not sufficient to maintain the production capacity of the production field. Make-up wells have to be drilled but wells are already densely drilled into the most productive part of the field. Thus, it is difficult to site a make-up well in the present field that will not affect wells that are already there. It is therefore desirable to expand the production area. The best possible make-up zones are the Gráuhnúkar reinjection zone and Hverahlíð in the southernmost part of the Hengill Area. Converting the Gráuhnúkar reinjection zone into a production field is not a straight forward task. The water that is reinjected there would have to be reinjected elsewhere and currently the injection capacity of the reinjection system barely meets the reinjection requirement for the Power-Plant. Moreover, it is not known how the reinjection that has been running from 2007 has affected the production capacity of the Gráuhnúkar zone. The Hverahlíð field is much more promising make-up field and it has recently been connected to the power plant.

Expanding the well field of the Hellisheiði Power Plant by including the Hverahlíð Field will certainly make it easier to operate the power production. It will offer more flexibility and it will be easier to site make-up wells, without affecting wells that are already in use. The biggest challenge now after the Hverahlíð Field has been connected is to gain a better understanding on the nature of the Hellisheiði field. The conceptual model of the Hengill Area has to be revised and the heat sources of geothermal systems have to be better understood. As mentioned above there are indications that the heat sources are at shallower depths than previously assumed. Reservoir parameters, such as permeability and porosity have to be studied further, as well as the effects of the production on the reservoir. This is mainly done using numerical modeling. However, numerical models are no better than their input (bullshit in, bullshit out) and in order to be able to predict how the reservoir responds to different production scenarios, one has to have an access to good quality data and a good conceptual model. Moreover, a good understanding of the geothermal system is necessary to find new methods of maintaining and optimizing production from the field.

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