

Managing the Production Fields in the Hengill Area

Gunnar Gunnarsson, Sigrún Tómasdóttir, Simon Klüpfel, Ásgeir Westergren, and Gísli Björn Björnsson

Orkuveita Reykjavíkur, Bæjarhálsi 1, IS-110 Reykjavík

gunnar.gunnarsson@or.is

Keywords: Hellisheiði, Nesjavellir, Hengill, reservoir management, reservoir modelling, make-up drilling, reinjection, economic feasibility, TOUGH2/iTOUGH2

ABSTRACT

The Hengill Central Volcano, SW-Iceland, contains widespread geothermal resources. Due to its proximity to Reykjavík those resources are of high importance for space heating in Reykjavík and surrounding communities and for electricity generation.

ON, a subsidiary of Orkuveita Reykjavíkur (Reykjavík Energy), operates two co-generation power plants in the Hengill Area; Hellisheiði in the southern part of the area and Nesjavellir on the northern flank of the Hengill Volcano. The current installed capacities of the power plants are 303 MW in electricity and 133 MW thermal for Hellisheiði and 120 MW in electricity and 290 MW thermal for Nesjavellir. The Nesjavellir Power Plant was commissioned in six phases in the years 1992-2006 and the Hellisheiði Power Plant in four phases in the years 2006-2011 and its production field was expanded in 2016.

The production density in the field is high or approximately 235 kg/s/km² (or 50 MW/km² in electricity) in the most productive part of the Hellisheiði Field. The production density in the most productive part of the Nesjavellir Field is similar. It is complicated to operate a geothermal field with such a high production density. In order to maintain reservoir pressure geothermal brine is reinjected into the reservoir and for maintaining production capacity make-up wells are drilled. Proper management of the fields requires being able to predict how the above-mentioned measures affect the geothermal reservoir.

To aid with decision making in the development and production from the geothermal fields in the Hengill Area, a numerical model of the entire Hengill area has been developed. It has been used to study the feasibility of different production scenarios and their impact on the geothermal reservoir. The model is constantly being revised and has been a key tool in the decision-making process for recent and future developments of the fields. Make-up drilling schemes and different reinjection schemes have been simulated. Building on those simulations, the economic feasibility of technically sound production scenarios has been estimated.

1. INTRODUCTION

The Hengill central volcano is located 30 km East of Reykjavík. Widespread geothermal resources are in the area and due to the proximity to Reykjavík and surrounding communities those resources are of high importance for space heating and electricity generation. Currently two co-generation power plants are operated in the Hengill Area. In the North is the Nesjavellir Power Plant and in the South is the Hellisheiði Power Plant.

A map of the Hengill Area is shown in Fig.1. It is a central volcano consisting of the Hengill Mountain and a SW-NE oriented fissure swarm on both sides of the mountain. Hot springs and fumaroles are widely found in the area. Three Holocene eruptions are known in the area, 2000, 5800 and 10'000 years ago. The eruptive fissures are found on the fissure swarm SW and NE of the highest part of Mt. Hengill. The Hengill Mountain itself and most of the area is a late Pleistocene hyaloclastite formation (Sæmundsson (1967); (1992); (1995)).

The well field of the Nesjavellir Power Plant is located in a rift valley on the fissure swarm just north of Mt. Hengill. The highest measured temperature is >380°C in a well in the northern part of the field. The geothermal system is mainly isolated from the upper groundwater layers by a cap rock layer of low permeability and there is a different water level (i.e. pressure) in those systems.

The Nesjavellir Power Plant was commissioned as a district heating utility plant in 1990. The initial installed capacity was 100 MW_{th}. A year later the installed capacity was expanded to 150 MW_{th}. In 1998 electricity generation capacity of 60 MW_e was installed and the thermal capacity was expanded to 200 MW_{th}. The installed electrical capacity was increased to 90 MW_e in 2001 and the district heating utility units reached its current capacity of 290 MW_{th} in 2003 (Gíslason et al. (2005)). The final step in developing the Nesjavellir Power Plant was taken in 2006 when the installed electric power was increased to 120 MW_e. Thus, the current installed capacity of the Nesjavellir Power Plant is 290 MW_{th} and 120 MW_e.

Apart from short trials, no injection of fluid into the geothermal reservoir itself takes place in the Nesjavellir field. The separated water (i.e. the brine) is disposed of into the lower parts of the ground water system above the cap rock separating it from the geothermal system. There are, however, plans of starting injecting separated water into the reservoir.

The Hellisheiði Power plant uses two drill fields. The main field – the Hellisheiði Field – is located on the fissure swarm SSW of Mt. Hengill. The other field – Hverahlíð – is located approximately 2 km SE of the Hellisheiði Field on the Eastern edge of the fissure swarm that intersects the Hengill Area. Those two fields are believed to be separate systems. As in the Nesjavellir field, the geothermal systems in Hellisheiði and Hverahlíð are separated from upper ground water layers by a low permeability cap rock.

The Hellisheiði Power Plant was commissioned in 2006 with installed capacity of 90 MW_e. It was expanded to 120 MW_e in 2007 and to 180 MW_e in 2008. In 2011 the installed electric generation capacity was expanded to 303 MW_e and a district heating utility

of 133 MW_{th} was commissioned. In the year 2016 the Hverahlíð field was connected to the Power Plant. The production capacity had been declining rapidly for a couple of years and it was necessary to enlarge the field. Since the Hverahlíð Field was connected to the Hellisheiði Power Plant the operation has gone more smoothly and the annual decline in production capacity is only half of what it was previously. The district heating utility was then expanded to 200 MW_{th} in 2020 to meet increasing demand for hot water.

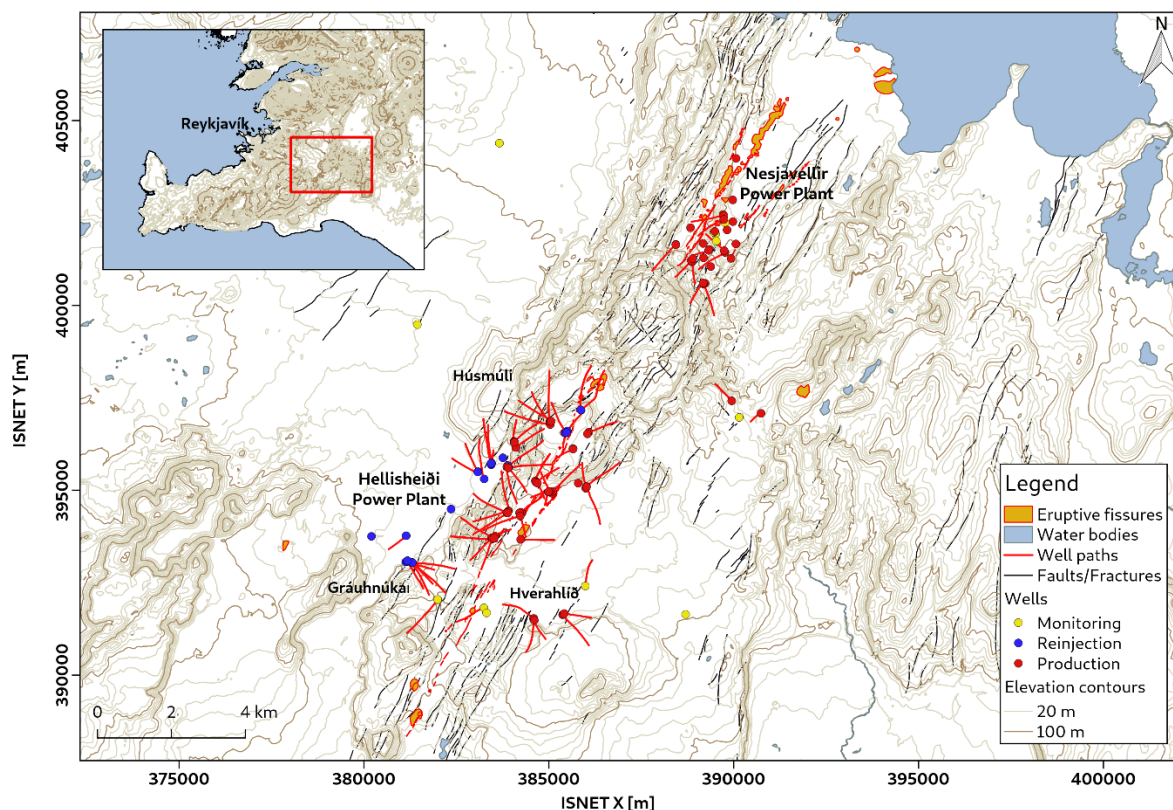


Figure 1: A map of the Hengill area showing elevation contours, surface fractures, eruptive fissures, production and reinjection wells as well as well paths projected to the surface. The inset shows the location of the area in SW-Iceland (Data Source: Reykjavík Energy and National Land Survey of Iceland)

Separated water thinned with condensate water is reinjected into the reservoir in the Hellisheiði Field. There are two main reinjection sites, Húsmúli and Gráuhnúkar. The injection provides pressure support and slows down the pressure draw-down in the field. There have been no signs of thermal break-through in production wells in the field.

A numerical model of the geothermal systems in the entire Hengill Area has been developed. It has been used as a tool in decision making, in estimating the status of the geothermal reservoir, and in addressing the sustainability of the geothermal utilization (see e.g. Björnsson et al. (2003); Björnsson (2006); Björnsson and Hjartarson (2005); Gunnarsson et al. (2011)). The model was developed using the TOUGH2/iTHOUGH2 software suite (Pruess et al. (2012); Finsterle (2007)). It has been calibrated to available field data and has been used to predict the effects of different production scenarios on the geothermal reservoirs and their production capacity.

2. PRODUCTION FROM THE GEOTHERMAL FIELDS IN THE HENGILL AREA

The production density is relatively high in all three fields that have been developed in the Hengill area. The production density (average flow pr. area [kg/s/km²]) for the fields in 2018 is shown in Fig.2. The production density in the Nesjavellir Field is approximately 250 kg/s/km² (see Fig.2 (a)) where it is highest. This is a considerably high production density and using the enthalpy of the produced fluid (~1600 kJ/kg) and the efficiency of the electricity generation this corresponds to a power density of 50 MW_e/km² in generated electricity. The average production density of the Nesjavellir Field is, however, approximately 75 kg/s/km², which corresponds to 15 MW_e/km². Despite the high production density, the operation of the Nesjavellir Power Plant has run relatively smoothly. The pressure drawdown has been steady and the need for make-up drilling has been on average one well every 3-5 years, which is according to plans. Thus, the lack of pressure support from injection has not been a problem. The recharge from surrounding formations, especially from the Northeast, has been believed to offer sufficient pressure support. Reinjection has, according to some modelling studies, been considered harmful for the production properties of the field (see e.g. Björnsson and Hjartarson (2005)). However, possible reinjection of separated water into the system is now being reviewed, due to environmental concerns with reinjection into shallow ground water layers. As a first step, reinjection into well NJ-18 on the Northwestern edge of the field was started in the end of 2018. The aim is to dispose of the separated water in an environmentally sound manner. It should be noted that the main environmental concern regarding injecting the separated water into ground water layers, as is the case now, is “thermal pollution” in Lake Þingvallavatn, not the toxicity of that water (Zarandi and Ívarsson (2010)).

The production is more complicated in the Hellisheiði Power Plant. The mass balance of the Hellisheiði Field is shown in Fig.2 (b). The distribution of the average production and injection combined (injection is positive and production negative) for the year 2018 is shown. The production is mainly concentrated on three areas; the NW part of Skarðsmýrarfjall, around the eruption fissures from Reykjafell towards Skarðsmýrarfjall, and in Hverahlíð. The highest production density in 2018 was around 235 kg/s/km². The average enthalpy of the produced fluid was around 1580 kJ/kg. Thus, the highest production density corresponds to a power density of 50 MW_e/km² in the turbines of the Hellisheiði Power Plant. The average mass production in the field is, however, around 62 kg/s/km² which corresponds to a power density of 14 MW_e/km².

The main difference of the operation of the Hellisheiði Field on one hand and Nesjavellir Field on the other hand is the injection into the Hellisheiði field. The separated water, thinned with condensate water is reinjected mainly into two reinjection sites; Gráuhnúkar, in the South and Húsmúli on the Western edge of the field. Water is also reinjected on the northern edge of the system and a small amount is reinjected in-field. In 2018, the average total flow of reinjected water into the field was 877 kg/s. The average flow of produced fluid from the field was 1248 kg/s. Thus, the net mass balance (flow of produced fluid minus reinjected water) of the system in 2018 was around 371 kg/s, i.e. 70% of the produced fluid was reinjected.

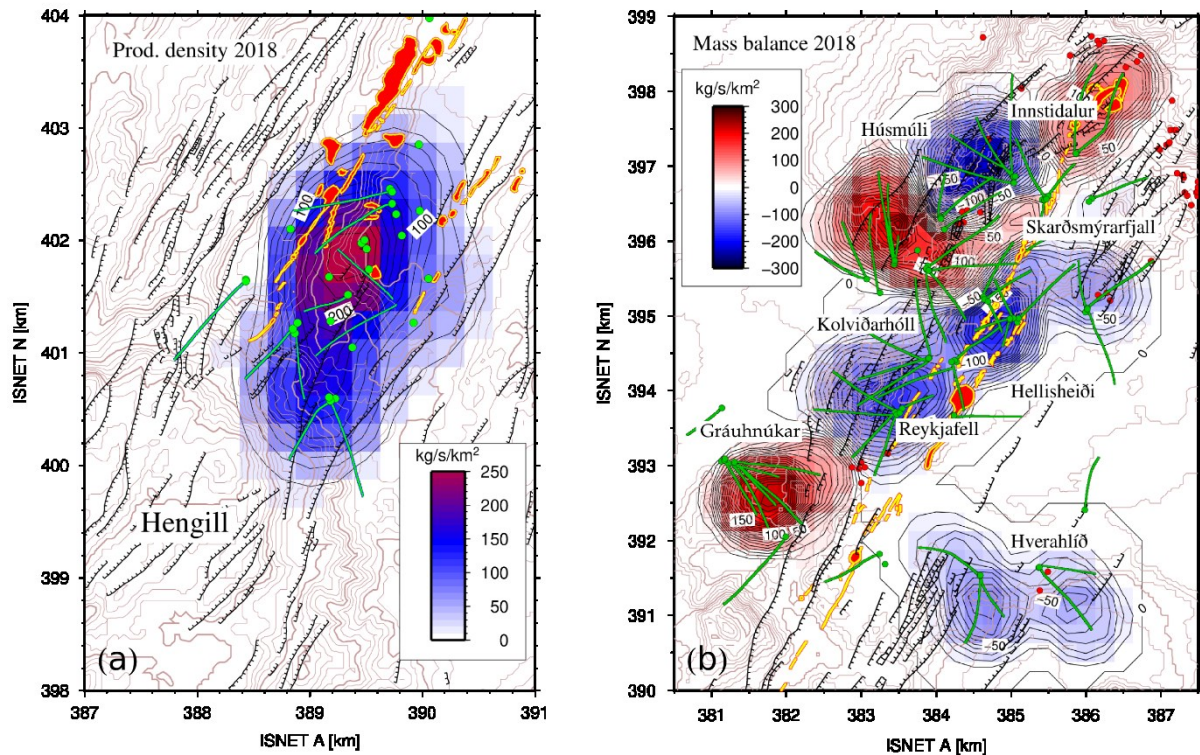


Figure 2: (a) Production density (mass flow pr. area) in the Nesjavellir Field in the year 2018. (b) Mass balance (production density and injection density combined) in the Hellisheiði Field in year 2018. Until recently, water has not been injected into the reservoir in Nesjavellir.

The production density in the geothermal fields in the Hengill Area is, as mentioned above, high (15 MW_e/km² in Nesjavellir and 14 MW_e/km² in Hellisheiði). As one can expect for such a high production density there is some decline in the production capacity of the fields; around 3-4% of installed capacity annually. In order to compensate for the production decline make-up wells are drilled. Injecting into the reservoir can also be useful in maintaining the reservoir pressure and thus, the production capacity. Injection can, however, be a double-edged sword. Thermal break-through, i.e. cold water from injection reaching production wells, can be harmful for the production. Even though a thermal break-through is not a problem, maintaining the pressure in the reservoir can result in a lower enthalpy. No thermal break-through has been recorded in the Hellisheiði Field. However, maintaining pressure has lowered the enthalpy in wells that yield high enthalpy fluid. The highest enthalpy in wells in the Hellisheiði Field is because of boiling in the formations, where the formation temperature is on the boiling point curve. Slowing down or even stopping the pressure draw-down will stop that boiling and thus, lower the enthalpy.

3. NUMERICAL MODEL OF THE HENGILL AREA

A numerical model has been developed of the entire Hengill Area, including the production fields in Hellisheiði, Hverahlíð and Nesjavellir, using the TOUGH2/iTOUGH2 software suit (Pruess et al. (2012); Finsterle (2007)). The lateral size of the model is 50x50 km and its vertical extent is from 2500 m below sea level (m b.s.l.) up to 400 m a.s.l. In the current version of the model, each layer consists of 3901 elements, which gives the total of 41'911 elements in the entire model. The total number of connections is 164'883. Fig.3 shows the layering structure of the model as well as the element structure in and around the production fields. The mesh is a Voronoi mesh created using the AMESH program (Haukwa, 1998). It is mainly hexagonal with an element size of 200 m (between centers) in the center of the mesh. The mesh gets coarser towards the edges of the model.

In general, the model elements that lie within the active geothermal system are assigned different “rock types” based on lithology, alteration, permeability and the reaction of the system to utilization. The part of the model that lies outside the geothermal system, the base of the model and the cap rock are given lower permeability. The cap rock is in layer C and in some areas deeper, i.e. in layer D (see Fig.3). An effective continuum method is used to model the fractured medium. This means that individual fractures are not specifically represented. Anisotropy in permeability is not modelled directly, even though one can expect the permeability in the fissure zone to be anisotropic. It is taken into account in the alignment of rock types and by inserting permeability barriers where data, tracer tests in particular, have shown strong anisotropy in permeability. Permeability barriers are yet only used in Hellisheiði, where extensive tracer tests have been conducted (Kristjánsson et al. (2016)). Currently, a tracer test is ongoing in Nesjavellir in connection with injection plans (Snæbjörnsdóttir et al. *this issue*).

The boundary conditions in the bottom layer drive the geothermal system. The temperature and pressure there is fixed and a small amount of hot fluid is injected into the bottom of the model in the areas with the highest temperatures. The heat sources are, thus, assumed to be below the model. The temperature and pressure is also fixed in the top layer.

The model is calibrated using initial pressure and formation temperature profiles of wells, and production history – i.e. pressure draw-down and enthalpy of the produced fluid. The permeability of the rocks within the geothermal system as well as the amount and enthalpy of the hot fluid injected at the bottom of the model are varied during the calibration. According to standard procedures in commercial geothermal reservoir modelling the heat sources drive the system into steady state before production is simulated (see e.g. O’Sullivan et al. (2001)). Steady state in this case means that the system is stable over a period of 10’000 years.

This method of simulating the heat sources, i.e. assuming that the heat sources of the system are below the system, and assuming steady state before production is simulated, has proven useful when simulating geothermal systems under production. Good fit can be obtained between measured and calculated parameters and it is possible to compare different production scenarios. There are, however, fundamental problems with those assumptions. Firstly, geothermal systems in volcanically active areas, like the Hengill Area, are very dynamic and 10’000 years is a long time in their history. As mentioned above three eruptions are known in the system in the last 10’000 years and one can expect that many intrusion events have occurred during that period. Secondly, a model that does not include the heat sources can hardly be called complete. There are also indications that the heat sources in the Hengill Area could be at much shallower depths than previously assumed – they might even reach the depth range of the model (Gunnarsson and Aradóttir (2015); Gunnarsson et al. (2017)).

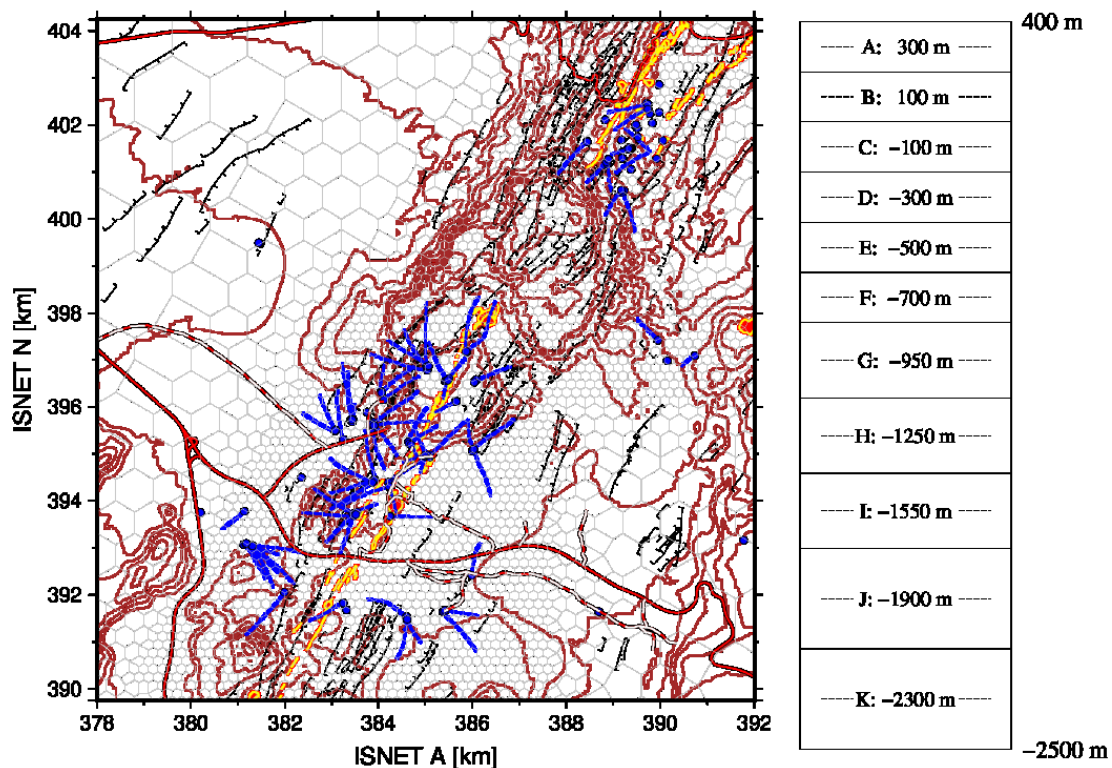


Figure 3: The elements in the center of the numerical model of the Hengill Area and the layering structure of the model. The grid is mainly hexagonal having finer element size in the center.

4. INVESTIGATING DIFFERENT PRODUCTION SCENARIOS

The model has been a useful tool in investigating different production scenarios, thus helping in decision making in operating the fields in the Hengill Area. The “do nothing” scenario, i.e. when production is maintained at maximum capacity and no make-up wells are drilled is often used as a reference in decision making. This scenario also serves as a health check of the operations. The results are compared to direct measurements on how the performance of the production wells has evolved. The annual decline in power generation capacity has been estimated to be around 3% in both fields.

In Fig.4 an example of a “do nothing” calculation for the Hellisheiði Field is shown. The five and ten year average of the decline of the electric power generation capacity is practically the same, i.e. $\sim 10 \text{ MW}_e/\text{y}$, or 3% as mentioned here above. The decline is mainly due to pressure drop in the reservoir but also due to changes in enthalpy (Sigurðsson et al. *this issue*).

Separated water is routinely injected into the reservoir in the Hellisheiði Field, but not in Nesjavellir. Different injection scenarios in Hellisheiði have been investigated using the numerical model, so have different make-up drilling scenarios (Gunnarsson et al. (2017)). Two examples of how the numerical model has been used will be discussed here. The first one is the current make-up drilling plan in Hellisheiði. The latter one is from Nesjavellir, where injection into the reservoir is being planned. The effect of hypothetical injection at the system periphery has been studied using the model.

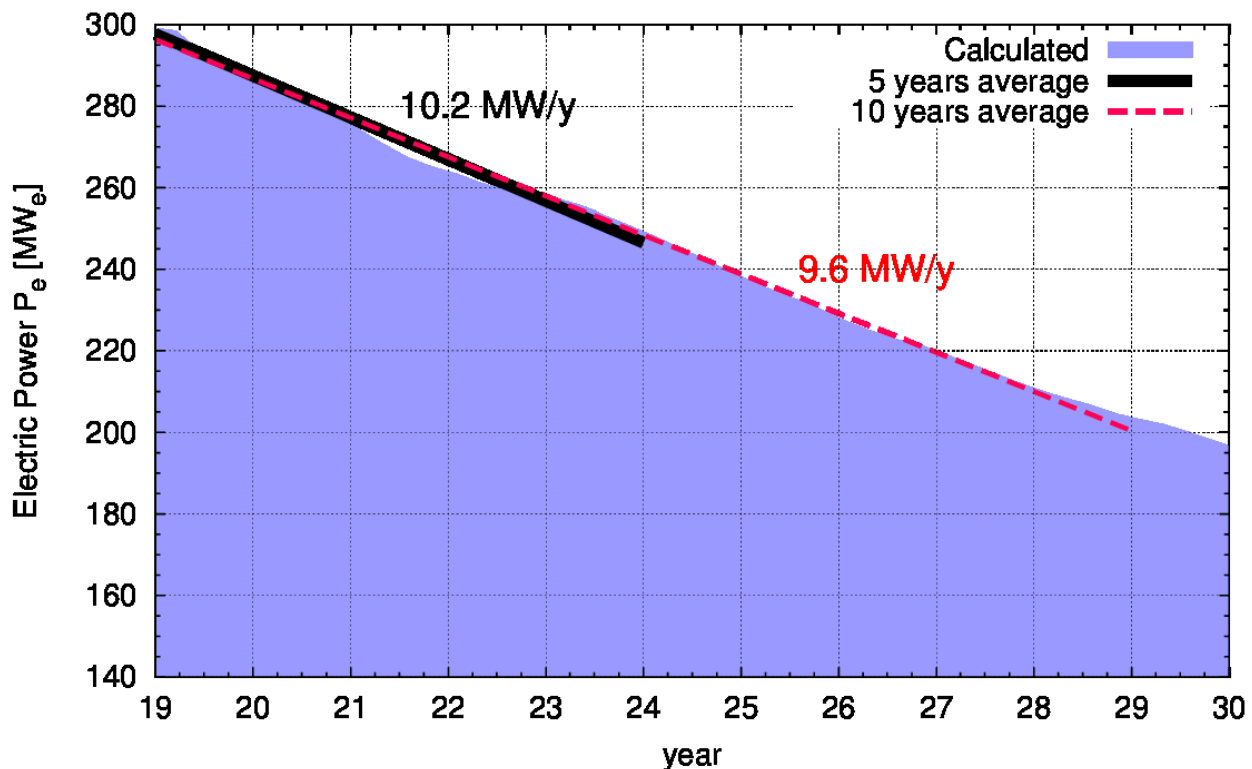


Figure 4: The declining production capacity of the Hellisheiði Field if no make-up wells are drilled. One can expect the electric generation capacity to decline about 10 MW_e annually which is $\sim 3\%$ of the installed capacity. This scenario (i.e. no make-up drilling) serves as the basic scenario in all decision making.

4.1 Make-up drilling in Hellisheiði

In order to maintain the production capacity of the field, make-up wells are drilled. The make-up drilling plans are simulated in the reservoir model in order to check their soundness; how many wells have to be drilled to maintain the production capacity and the economic feasibility of the drilling plan. The current make-up drilling plan was organized in the years 2015 and 2016. It was estimated that about 15 wells would have to be drilled till 2026 in order to maintain the production capacity of the Hellisheiði Power Plant. That 15 well drilling plan was the base scenario when estimating the cost per MW_e generated.

Two other scenarios were also investigated; one pessimistic and one optimistic. In the optimistic scenario it was assumed that the decline rate of the production capacity was relatively low. Thus, less wells would have to be drilled in order to maintain the production capacity of the power plant, or 6. In the pessimistic scenario the decline rate was high, so more wells, 32 in total, had to be drilled to maintain the power plant’s production capacity. These three scenarios were investigated and their economic feasibility was estimated. What was interesting in this study was that all scenarios turned out to be profitable, and even the pessimistic scenario was better than the “do nothing” scenario (Gunnarsson (2017)).

In 2019, during the third year of the drilling plan, it was interesting to compare the results of the drilling to the original estimates. At that time, four wells had been completed in the Hellisheiði Field and two more were scheduled. In Fig.5 the economic feasibility of the current plan is compared to the originally estimated scenarios. The normalized cost per MW_e from make-up wells is plotted for all scenarios vs. time. It is interesting to see that the cost pr. MW_e for the current plan is almost the same as for the optimistic scenario. The reason for this is that two of the first wells drilled according to the plan were very successful. They yield more than 20 MW_e of electric power each, which means that each well equals approximately 4 average production wells in the geothermal fields of the Hengill Area.

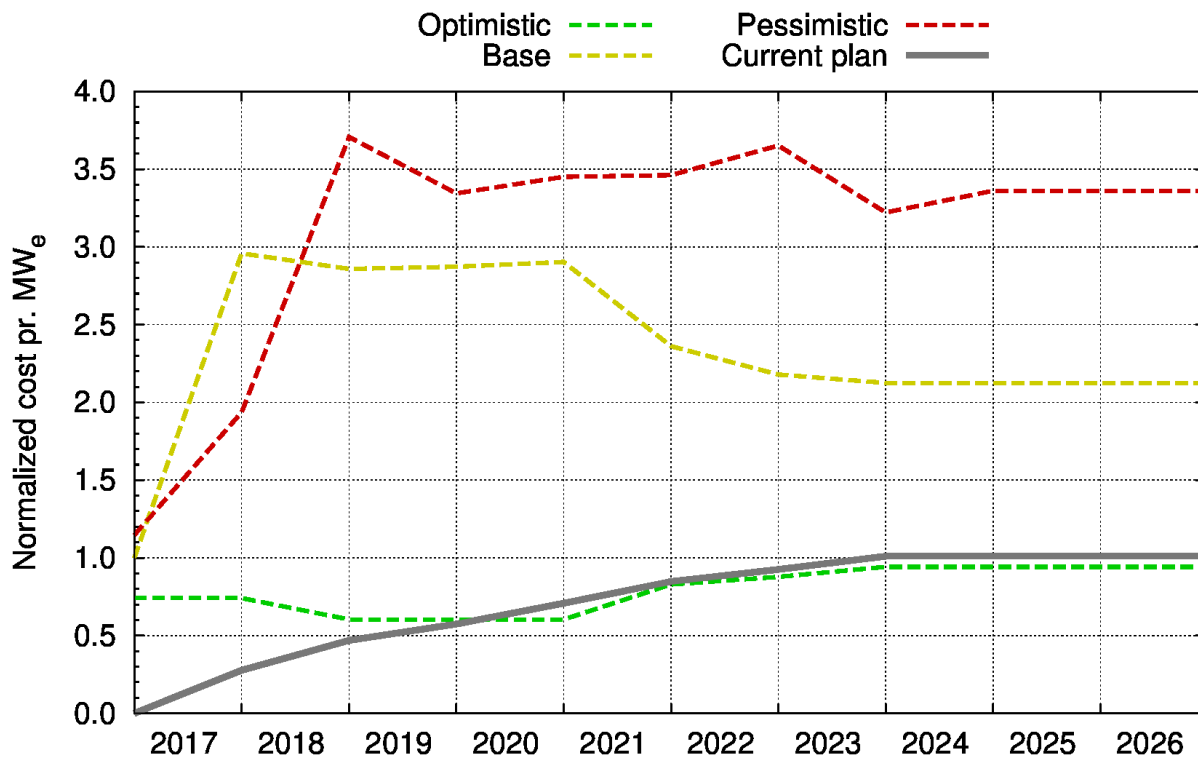


Figure 5: The economic feasibility of different simulated production scenarios compared to the current make-up drilling plan. Normalized cost per megawatt is shown. When planning the make-up drilling in the Hellisheiði Field three different scenarios were investigated: The *base* scenario, i.e. the scenario with the most “realistic” drilling success rate. Two other scenarios are also shown: One *pessimistic*, with low drilling success, and one *optimistic* with high drilling success.

4.2 Injection in Nesjavellir

Reinjection into shallower groundwater layers in Nesjavellir has resulted in thermal pollution in Lake Þingvallavatn (Zarandi and Ívarsson (2010)). Because of this, deep reinjection into the geothermal reservoir is now being considered. As mentioned above, previous modeling studies have indicated that reinjection into the reservoir could have undesired effects on the production properties of the field. The formation temperature in many wells in Nesjavellir is close to the boiling point curve. Pressure draw-down due to production causes boiling which in turn increases the enthalpy of the produced fluid. As mentioned in section 2, decreased draw-down, or increased pressure, can decrease boiling and by that decrease the enthalpy of the produced fluid. To minimize this effect, plans for deep reinjection aim at injecting at the systems Northeastern periphery.

The numerical model was used to study the effect of such reinjection on the production properties of the system. However, knowledge on the conditions of the system at that periphery is limited since no drilling has taken place there. Formation temperature in well NJ-18 is lower than in the wells in the center of the production zone, but there are no wells to constrain the formation temperature Northeast of that well. In the current simulation model, the Northeastern end of the geothermal system rock types are assumed around well NJ-18. The proposed sites for future reinjection wells are, however, further to the North and thus lie outside the geothermal system in the current simulation model. When it comes to modeling the effect this reinjection would have, the validity of the assumption of the edge of the geothermal system becomes vital. To test the effect of the current rock type setup, three different scenarios were set up. All scenarios test the effect of injecting 150 kg/s into two hypothetical wells, 75 kg/s into each. In these simulations, injection was started in the year of 2010 and the results were compared to simulations where no injection took place. The factor that varies between scenarios is the extent of the geothermal system towards the Northeast. In the first scenario, the geothermal rock types in the current simulation model are used, in the second one, the system is extended so that the hypothetical reinjection wells fall within it and in the third scenario, the geothermal system rock types are extended all the way to Lake Þingvallavatn. This setup is shown in Fig.6(a). For simplicity, the subdivisions of the rock types within the geothermal system are not shown, only the overall system boundaries. The location of the hypothetical injection wells is shown with yellow stars.

The results from the simulations are shown in Fig.6(b-d). In the first scenario, fluid is reinjected into the less permeable outer formation and is therefore not in great hydrological connection with the production zone. Because of that, the effect on the production properties of the field is not very pronounced. The draw-down in well NJ-18 decreases slightly and the enthalpy as well, but the effect is minimal. In the second scenario, fluid is injected into the edge of the system. The effect on the average weighted enthalpy is very clear and appears immediately when injection is started and after 8 years it has dropped by approximately 200 kg/kJ. The draw-down also shows a clear jump when injection is started. In the third scenario, the system is extended even further so the injected fluid can easily flow towards the Northeast as well, that is, it is less constrained by the lower permeability outer formation. In this case, the same clear signal is observed but the reduction in enthalpy and draw-down is smaller than in scenario 2. What is also apparent from the simulations is the lowering average weighted enthalpy between the scenarios. That is, the overall enthalpy is highest in scenario 1, lower in scenario 2 and the lowest in scenario 3. Over the period shown in the figures, the yearly weighted average of the measured enthalpy from the wells in Nesjavellir has ranged from slightly over 1600 kg/kJ to about 1850 kg/kJ. Considering that, the last scenario

seems the least likely. These simulations show the large effect the hydrological connection of the future reinjection site to the production zone has on the response of the system to reinjection.

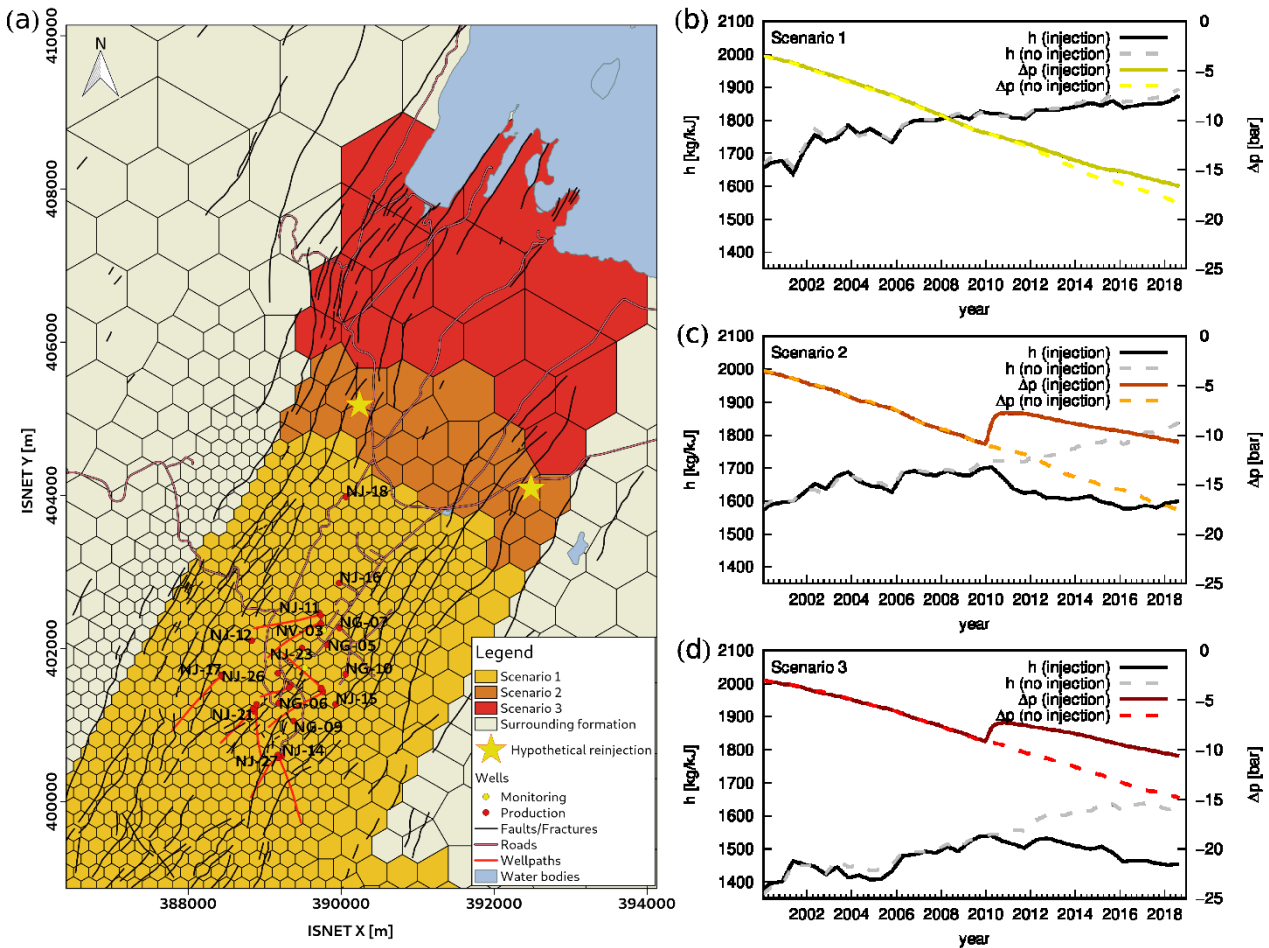


Figure 6: (a) The setup for the three different simulation scenarios. Scenario 1 (yellow) shows the current extent of the modelled geothermal system, scenario 2 (orange) shows the system extended to the Northeast so it encloses the hypothetical injection wells, scenario 3 (red) is extended even further so it reaches Lake Þingvallavatn. The injection wells are shown with yellow stars (b-d) Simulated average weighted enthalpy from all wells in Nesjavellir as well as the simulated draw-down in well NJ-18. Dashed lines show the results when no injection took place and the solid lines show the results when hypothetical reinjection was introduced in 2010.

This preliminary study exemplifies the limitations of reservoir modeling when it comes to simulating conditions far away from the actual data points (i.e. wells). Despite being able to use indirect measurements, such as resistivity measurements, to estimate the size of the geothermal system, the model is not well constrained far away from the wells. The only way to obtain measurements on the main properties of the geothermal reservoir and the reservoir fluid is via drilling. Resistivity measurements still indicate that the Northern boundary of the Nesjavellir Field is around well NJ-18 (Árnason et al. (2010)). Thus, it is a reasonable guess to assume that scenarios 1 and 2 are closer to reality than scenario 3. The results from planned tracer tests might shed some light on the extent of the system towards the Northeast.

5. SUMMARY AND CONCLUSION

Two geothermal power plants are operated in the Hengill Area; Nesjavellir in the North and Hellisheiði in the South. Both are co-generation power plants producing both electricity and hot water for space heating. The production density in the geothermal fields in the Hengill Area is relatively high or 14-15 MW/km². The production capacity declines around 3-4% of installed capacity annually. In order to compensate for that decline, make-up wells are drilled, geothermal fluid is reinjected into the system, and the production zone has been enlarged by incorporating geothermal resources on the edge of the fields or in their vicinity to the well field, and thus, spreading the production over a larger area.

Drilling make-up wells is a standard procedure in operating geothermal fields and it often constitutes the biggest part of the operational cost. It's therefore essential to have reliable estimates on the decline rate of the fields' production capacity in order to be able to predict how sound the operational plans are economically. The drilling strategy for the Hellisheiði Power Plant included 15 make-up wells that were to be drilled till 2026. For assessing the risk of that plan two other scenarios were investigated; one pessimistic with higher decline rate, and one optimistic, with low decline rate. The first wells that were drilled according to the make-up drilling plan were extraordinary successful. Therefore, the cost per MW_e is now as was expected in the optimistic scenario. Predicting the success of drilling a well is hard – especially when drilling in a relatively new field. Those two aforementioned wells were drilled in the

Hverahlíð Field, which was commissioned in the beginning of year 2016. Of the five wells that had been drilled there at that time, four were usable and the average power estimates of all five wells was estimated 11.5 MW_e, which is reasonably good. In spite of those good results, nobody expected the two next wells to be so powerful (yielding more than 20 MW_e each).

Numerical simulations show that the effect of reinjection into the deep geothermal system in Nesjavellir is very dependent on the extent of the geothermal system. If the injection takes place outside the permeable geothermal system, it will have minimal effect on the production properties of the system. If the injection wells are however in good hydrological connection to the production wells, pressure increase and decreased draw-down within the production zone can cause a decline in fluid enthalpy. The simulations carried out in this study show the limitation of the numerical model when it comes to predicting conditions far away from existing wells.

Operating power plants in a complicated geothermal field is a challenging task requiring an interdisciplinary approach. There are many factors that control what is technically and economically feasible at each time. Understanding the dynamics of the geothermal system is essential in this aspect and reservoir modelling plays a key role in that. Outer factors, such as energy prices, demand, regulations etc. are also important parameters in this respect. Thus, it is of great importance to incorporate all these factors when estimating feasibility of different production schemes.

REFERENCES

- Árnason, K., Eysteinnsson, H., and Hersir, G.P.: Joint 1D inversion of TEM and MT data and 3D inversion of MT data in the Hengill area, SW Iceland. *Geothermics* **39**, (2010), 13-34
- Björnsson, G., Hjartarson, A., Böðvarsson G., and Steingrímsson, B.: Development of a 3-D geothermal reservoir model for the greater Hengill volcano in SW-Iceland. Proceedings of TOUGH Symposium 2003, Lawrence Berkeley National Laboratory, Berkeley, California, May 12-14, (2003).
- Björnsson, G. and Hjartarson, A.: Nesjavallavirkjun: Endurkvörðun reiknilíkans og spár um viðbrögð jarðhitakerfis við stækkun raforkuvers úr 120 í 150 MW (The Nesjavellir Power Plant; Recalibration of Numerical Model and predicting the reaction of the geothermal reservoir to enlarging the power production from 120 MW to 150 MW.) ISOR-2005/001, (2005).
- Björnsson G.: Applying the Hengill Geothermal Reservoir Model in Power Plant Decision Making and Environmental Impact Studies, Proceedings of TOUGH Symposium 2006 Lawrence Berkeley National Laboratory, Berkeley, California, May 15–17, (2006).
- Finsterle, S.: iTOUGH2 User's Guide, Lawrence Berkeley National Laboratory, Berkeley, California, (2007).
- Gíslason, G., Ívarsson, G., Gunnlaugsson, E., Hjartarson, A., Björnsson, G., and Steingrímsson, B.: Production monitoring as a tool for field development, a case history from the Nesjavellir Field, Iceland. Proceedings World Geothermal Congress 2005, Antalya, Turkey, 24-29 April 2005, (2005).
- Gunnarsson, G. and Aradóttir, E. S.: The Deep Roots of Geothermal Systems in Volcanic Areas: Boundary Conditions and Heat Sources in Reservoir Modeling. *Transp Porous Med*, **108**, (2015), 43-59
- Gunnarsson, G., Arnaldsson, A., and Oddsdóttir, A.L.: Model Simulations of the Hengill Area, Southwestern Iceland, *Trans Porous Med*, **90**, (2011), 3-11
- Gunnarsson, G., Westergren Á., and Björnsson G.B.: Numerical simulations and decision making in the Hellisheiði Geothermal field, SW-Iceland, *GRC Transactions*, **41**, (2017), 2743-2758
- Haukwa, C.B.: AMESH. A mesh creating program for the Integral Finite Difference Method: User's Manual, Earth Sciences Division, Ernest Orlando Lawrence Berkeley National Laboratory, (1998).
- Krisjánsson B.R., Axelsson, G., Gunnarsson, G., Gunnarsson, I., and Óskarsson, F.: Comprehensive Tracer Testing in the Hellisheiði Geothermal Field in SW-Iceland, Proceedings, 41th workshop on Geothermal Reservoir Engineering, Stanford University, February 22-24, (2016), SGP-TR-209
- National Land Survey of Iceland: Niðurhalsþjónusta [Download service], (2018).
- O'Sullivan, M. J.; Pruess, K.; and Lippmann, M. J.: State of the art of geothermal reservoir simulation, *Geothermics*, **30**, (2001), 395-429
- Pruess, K., Oldenburg, C. and Moridis, G.: *TOUGH2 User's guide, Version 2*. (LBNL-43134). California: Lawrence Berkeley National Laboratory, (2012).
- Zarandi, S.S.M.M. and Ívarsson, G.: A Review on Waste Water Disposal at the Nesjavellir Geothermal Power Plant, Proceedings World Geothermal Congress 2010, Bali, Indonesia, 25-29 April 2010, (2010).
- Sigurðsson, P., Gunnarsson, G., Galeczka, I.M., Einarsdóttir, Í.E.: Changes in Production Capacity at Hellisheiði and Nesjavellir Geothermal Power Plants, Proceedings World Geothermal Congress 2020, Reykjavík Iceland, 26 April – 2 May, 2010, (this issue)
- Snæbjörnsdóttir, S.Ó., Galeczka, I.M., Sigfússon, B., and Oelkers, E.H.: Injection of geothermal CO₂ and H₂S gases at the Nesjavellir Site: A pre-injection overview, Proceedings World Geothermal Congress 2020, Reykjavík Iceland, 26 April – 2 May, 2010, (this issue)
- Sæmundsson, K.: Vulkanismus und Tektonik des Hengill-Gebietes in Südwest-Island. Ph.D. thesis, Universität zu Köln, (1967).
- Sæmundsson, K.: Geology of the Thingvallavatn area. *OIKOS*, **64**, (1992), 40-68.
- Sæmundsson, K.: Hengill, Geological Map (bedrock) 1:50.000, (1995).