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Changes in Production Capacity at Hellisheiði and Nesjavellir Geothermal Power Plants

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ABSTRACT

There are two geothermal power plants built around Hengill central volcano, at Nesjavellir and Hellisheiði. Thermal production began at Nesjavellir in 1990 and electrical production in 1998. Nesjavellir power plant reached its current capacity in 2005, with installed capacity of 120 MW_e and 290 MW_{th}. Production at Hellisheiði began in 2006 and since 2011 the installed capacity has been 303 MW_e and 133 MW_{th}.

Production is monitored at both power plants. The monitoring has increased since the beginning of production and is substantial. Changes in production capacity are monitored with two different and independent methods. One method relies on measurements of power outputs of geothermal wells and comparison of those measurements. The other method simulates and forecasts the changes in production over a certain period, using production data, pressure monitoring, temperature monitoring and more. The outputs of the two independent methods are then represented as two figures and as a combined result, the latter with uncertainties of both methods.

The power output and chemical composition of production wells are measured up to twice a year. The method used is a tracer fluid test (TFT). There are two different types of tracers used, one for the vapor phase and one for the liquid phase. Both tracers are injected in the stream of geothermal fluid coming up a production well, close to or inside the wellhead. Samples of the geothermal fluid are taken further downstream and the dilation of both tracers measured. From there the mass flow of each phase, and therefore the enthalpy, is known. Productivity curves for each well are fitted to the measured data. The annual changes in production capacity are then calculated by using a productivity curve, enthalpy and levelized wellhead pressure for each production well.

The forecast method relies on newest data on production, power output of production wells, temperature and pressure changes in the reservoir and more. The model itself and input values are update every year. From the input values and a calibrated model, a production capacity is calculated and state of the reservoir estimated. Assumptions are made that there are no make-up wells or any other changes in operation during the predicted period. Therefore, results of the simulations are predicting the state of the geothermal reservoir and production capacity after a certain period.

Results from both methods are compared and represented as a single value for changes in production capacity. The value is represented with limits of uncertainty, estimated from both methods. Results from the methods are updated once or twice a year and utilized in decision making processes in terms of the need for drilling make-up wells, actions related to more evenly distributed production and more.

1. INTRODUCTION

The Hengill central volcano is located 30 km East of Reykjavík and is known for the widespread geothermal resources in the area. Those resources are of high importance for space heating and electricity generation for close-by towns and municipalities. Currently two combined heat and power (CHP) plants are operated in the Hengill Area. In the North is the Nesjavellir Power Plant and in the South is the Hellisheiði Power Plant.

The well field of the Nesjavellir Power Plant is in a rift valley on the fissure swarm just north of Mt. Hengill and consists of 31 deep wells (>1000 m depth) and 9 shallow injection wells. Out of the 31 deeper wells, 21 are connected to the steam gathering system and 1 is being tested as a deep injection well. The Nesjavellir Power Plant began as a district heating 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 production began with generation capacity of 60 MW_e 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 it 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 capacity was increased to 120 MW_e. The current installed capacity of the Nesjavellir Power Plant is 290 MW_{th} and 120 MW_e.

There are two well fields for the Hellisheiði Power plant. The main field is in the vicinity of Hellisheiði Power Plant, 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 consist of 61 deep wells drilled for production purpose and 17 injection wells. Out of the 61 deep wells, 46 are connected to the steam gathering systems and 3 are injection wells. The fields are believed to be separate systems. The Hellisheiði Power Plant was commissioned in 2006 with installed capacity of 90 MW_e. It was expanded to 123 MW_e in 2007 and to 213 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 2016 the Hverahlíð field was connected to the Power Plant.

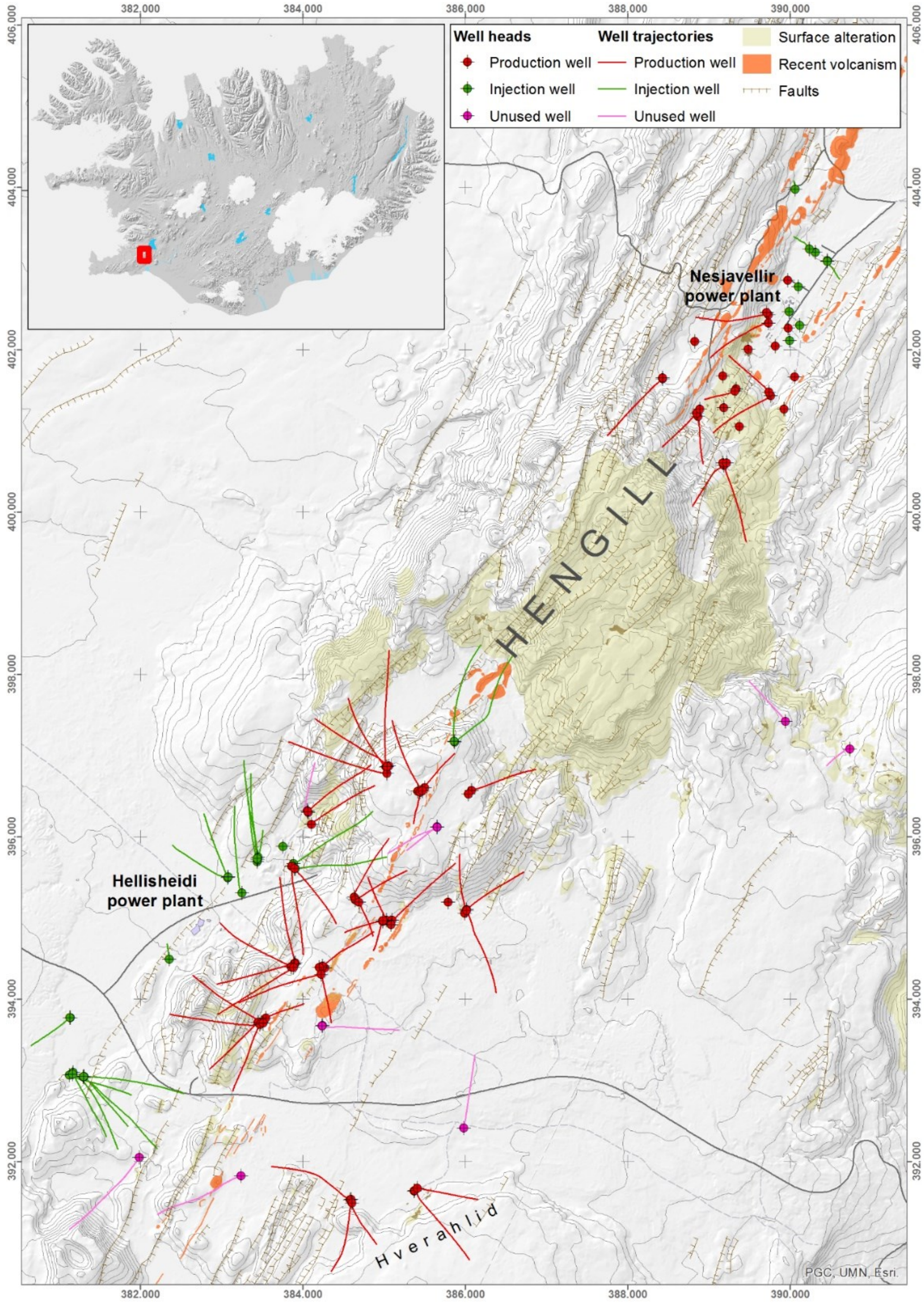
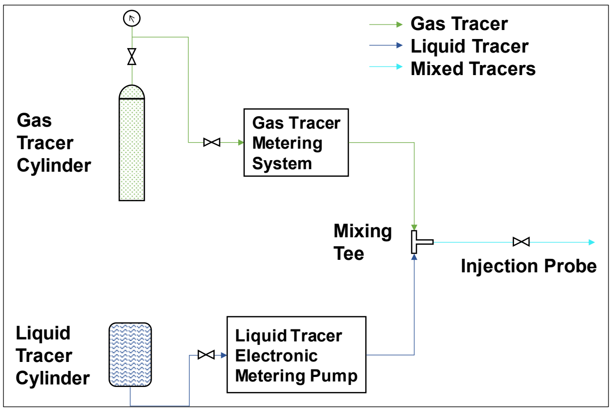


Figure 1: A map of the Hengill area showing elevation contours, surface fractures, eruptive fissures, production and reinjection wells as well as well paths projected to the surface. The inset shows the location of the area in SW-Iceland

2. MONITORING PRODUCTION IN HELLISHEIÐI AND NESJVELLIR GEOTHERMAL FIELDS

The production at both power plants is monitored in numerous ways. There are continuous monitoring systems in and around the power plants, most of which are recording pressure, temperature, single-phase mass flow rate and other aspects related to electrical and thermal production. Related to production, the single-phase mass flow rate monitoring is most relevant when monitoring the amount of fluid coming up from the reservoir but it does not help to understand where the fluid is coming from. Out in the field there is continuous pressure and mass flow monitoring on injection wells, but only pressure monitoring on some production wells. The continuous wellhead pressure system on production wells is still expanding. In the meantime, there is weekly or bi-weekly wellhead pressure monitoring for each production well, carried out with manual pressure gauge measurements.

Power output in each production well is measured once or twice a year with a tracer fluid test (TFT). The equipment used is from and has been developed by Thermochem®, an integrated consultancy, service and OEM instrument firm. The system, Thermochem's MicroMod TFT®, is a simple, cost-effective, portable and is usable throughout a wellfield or a power plant (Thermochem, 2018). The liquid-phase tracer used is 10 % ThermoTrace™ solution and the gas-phase tracer is 1-2% solution of SF_6. The tracers are pumped through the MicroMod TFT® system while the quantity of each tracer is measured. The tracers are injected into the two-phase flow coming from a production well and samples of each phase are taken 20 – 40 m down stream of the injection point, using a Webre-type separator, see Figure 2 (Arnórsson, 2000). The steam is collected into evacuated one port Giggenbach bottle filled with 50 mL 40% NaOH (Ármansson and Ólafsson, 2006). The CO_2 and H_2S dissolve in the NaOH, whereas the SF_6 and other gases are concentrated in the head space. The water is collected in a 500 mml bottle over a 1 min period and stored in a 100 ml brown-stained glass bottle, allowing little light penetration. The samples are then sent for analysis, the tracer in the liquid-phase is analyzed at Reykjavík Energy and the analysis for the vapor-phase tracer is done by Iceland GeoSurvey.



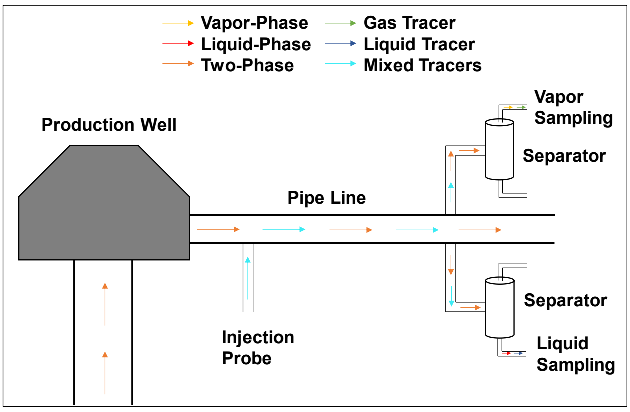


Figure 2: Left, diagram the MicroMod TFT® system from Thermochem®. Rigth, diagram of in-situ TFT setup and sampling equipment used at Hellisheiði and Nesjavellir geothermal fields.

A spectrometer is used to analyze ThermoTrace in liquid-samples, called ThermoTrace Analyzer (TTA). There excitation light goes through the sample and the fluorescent signal emitting from the sides and measured with a CCD detector. It is necessary to calibrate the range of the TTA every day when analyzing. The calibration is performed with DI water and dissolved 10% ThermoTrace working solution (100 ppb). All standards must be prepared from the same solution as the injection tracer where true concentration of the tracer is found by average concentration of four dilutions. Four standards are prepared, total volume is 10 ml, 9 ml of background brine, taken the same day as the samples, and then 1 ml combination of DI water and Thermo Trace working standard (Thermochem, 2015). Usually the tracer concentration in the samples is under 500 ppb. If it is over 500 ppb all the samples must be diluted. Collected and analyzed samples are nine, eight Thermo Trace samples and one background brine, or a blank.

The SF_6 analysis is performed using a gas chromatograph, Thermo Scientific TRACE-1310, equipped with an electron capture detector (ECD) and controlled by Chromeleon software. Nitrogen (5.0, 99.999%) is used as a carrier gas with an inlet pressure of about 65 psi. The gas sample is transferred from a sampling bottle, Giggenbach bottle, through a customized inlet line of known volume into the instrument injection ports. The sample together with the carrier gas passes through an analytical column, TG BOND alumina Na_2SO_4, where the SF_6 gas is separated from other gases to a detector at 300° C. The SF_6 is quantified using 1, 5, 10 ppm SF_6 (v/v) standards depending on sample concentration.

From the analysis the concentration of each tracer is known and thus the mass flow rate of steam, brine and the enthalpy of the fluid from each well can be calculated:

$$Q_{L,V} = \frac{Q_T}{(C_T - C_b)} \tag{1}$$

Where $Q_{L,V}$ is mass flow rate of fluid, liquid and vapor respectively, Q_T is tracer injection mass flow rate, C_T is the measured tracer concentration by weight and C_B is the measured background concentration. The enthalpy is calculated using the heat and mass balance equation where the known enthalpies of liquid and steam for a given separation or sampling pressure are derived from steam tables:

$$H_F = \frac{(Q_V \times H_V) + (Q_L \times H_L)}{Q_F} \tag{2}$$

Where Q_F is mass flow rate of the fluid, summary of vapor and liquid mass flow rate and $H_{V,L}$ is the enthalpy of saturated vapor and liquid, respectively, at separation or sampling pressure (Hirtz et al., 1993). The results, total mass flow rate and enthalpy, are used to develop or revise a productivity curve for each production well. A productivity curve for a production well represents the relationship between total mass flow rate and wellhead pressure, usually represented with a second- or third-degree polynomial (DiPippo, 2012):

$$Q_T = P_{wh}(Q_T) = a_3 \times {P_{wh}}^3 + a_2 \times {P_{wh}}^2 + a_1 \times P_{wh} + a_0 \tag{3}$$

Where Q_T is total mass flow rate, P_{wh} is wellhead pressure and $a_{3,2,1,0}$ are coefficients which are calculated from the dataset with a fitted curve. The newest data is used to develop the productivity curve for a production well, therefore with new data the productivity curve is revised. From this relationship, the total mass flow rate is calculated for a measured wellhead pressure. By assuming constant enthalpy from newest TFT result, the mass flow of liquid and vapor are known. The productivity curve for a production well in utilization is revaluated once or twice a year, as often there are new TFT results.

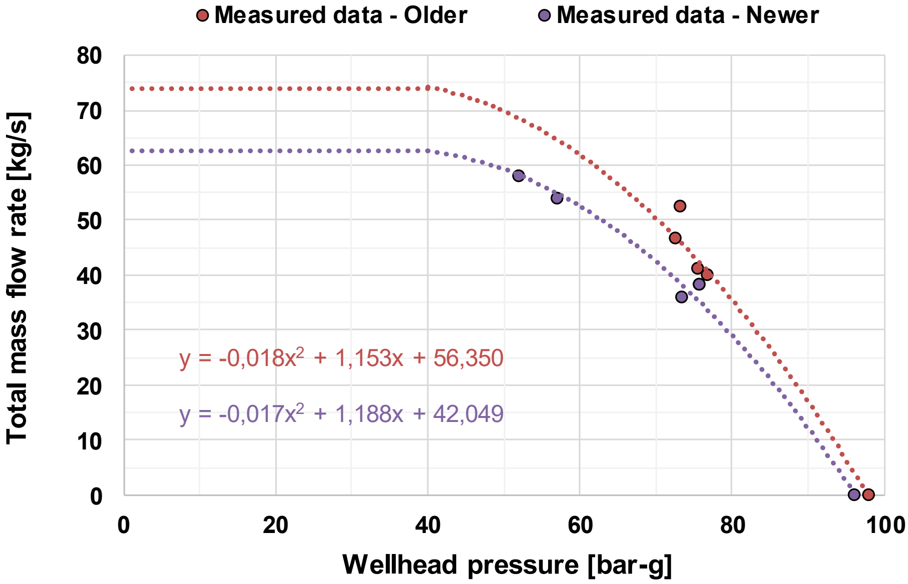


Figure 3: Productivity curves, dotted lines, for a production well in Hverahlíð, one of two well fields for Hellisheiði Power Plant. The curves are fitted to the available data. In the beginning, the well was not tested with wellhead pressure lower than 70 bar$_g$, increasing the uncertainty of the productivity curve (red dotted line) below that pressure. Initial estimations of the productivity curve were over optimistic when compared to newest data (purple dotted line). Although it is not known, both productivity curves are estimated to flatten out after 40 bar$_g$ due to choked flow in well, restricting more mass flow.

A productivity curve is formulated for each production well at both Hellisheiði and Nesjavellir Power Plants. By knowing the pressure for each well, the total mass flow rate of each well is known and therefore the total amount of fluid being extracted from the reservoir. The total amount is then compared to the summation of certain single-phase flow meters, both vapor and liquid. The calculated amount of the vapor-phase is often comparable to the measured amount, within 3% error margin, whereas the calculated amount of the liquid-phase has a high margin, around or more than 5% error margin from the measured amount. From the time-series of wellhead pressure, either the continuous monitoring or the bi-weekly manual monitoring, the total amount of fluid extracted from the reservoir is calculated for a given period, a month, a year or more. By calculating the total amount of injection fluid, from the single-phase flow monitors, the return-ratio for each period is calculated as well as production distribution, an important tool to monitor the reservoir and for decision making regarding production.

Another important tool gotten from the productivity curves is the production capacity. It can be calculated from the current wellhead pressure but also by defining the lowest possible wellhead pressure, or levelized wellhead pressure, for each well, therefore calculating the maximum output. With the maximum output, the maximum production capacity at a certain time is known. Knowing the production capacity of the gathering system is important in planning ahead, making sure there is enough steam for the turbines to run at full capacity. Therefore, estimating the changes in the production capacity are as important.

3. CHANGES IN PRODUCTION CAPACITY

The changes in production capacity are a vital index for Hellisheiði and Nesjavellir Power Plants. The changes are derived from two different methods. One method relies on measurements of power outputs of geothermal wells and comparison of those measurements. The other method simulates and forecasts the changes in production over a certain period, using production data, pressure monitoring, temperature monitoring and more. Both methods rely on results from TFT but for the forecast method, or numerical modeling, the enthalpy is an input to a calibrated model whereas the former method compares newest results to older. Both methods give a result on how the capacity changes on a yearly basis. For simplification, results from both methods are represented as a single value for changes in production capacity per year.

2.1. Maximum power output from productivity curves

After TFT analysis, a productivity curve is formulated or revaluated for each production well. By knowing the minimum wellhead pressure for each well, or the levelized wellhead pressure, the maximum output of each well is known. The summation of maximum output gives a value which represents the maximum production capacity. As the TFT measurements are done once or twice a year, the data and knowledge on maximum production capacity changes. These changes show a decline in production capacity, roughly 3% per year, but when new production wells are drilled and connected to the gathering system, the production capacity increases, see Figure 4 and Figure 5.

Evaluation of decline in production capacity is done by comparing the same wells between certain time periods, excluding newly drilled wells. It is done in two ways, by comparing the maximum production capacity of all production wells or by comparing maximum power output of each well and summarizing the total change of the system. In the latter, comparison is done between evaluations of maximum capacity for a certain time, when the TFT is performed, thus having a more precise comparison of time than the former method. The latter method is utilized and thus the summation of decline of each well represents of the decline for the whole gathering system. As of today, the comparison is done between two dates, two newest TFT results, and therefore the decline for each well is the slope between the two dates. Another method, a linear regression approach, would be to take more TFT results into consideration where the decline would be the slope of the best fitted line for the available data. A work is in progress to use the more than two dates for each well, reducing the weight of each datapoint and the fluctuation in production capacity changes.

For Hellisheiði Power Plant, the decline in production capacity is either represented for each steam gathering field, Hverahlíð and Hellisheiði, or as total decline. Both representations are useful and are vital information for planning, both for the production side and the drilling of new production wells, or make-up wells. The total decline has been around 3% last 3 years. The decline in Hellisheiði steam gathering field has been lower than 3% but higher in Hverahlíð, due to short production history. For Nesjavellir Power Plant, the decline in production capacity was estimated to be roughly 2% but as of today, the decline is around 3%. The change was recognized in 2016-2017 and was estimated to be the consequence of deep injection of heated-up groundwater but looking back at maximum production capacity, the change started 2014-2015 or sooner, see Figure 5.

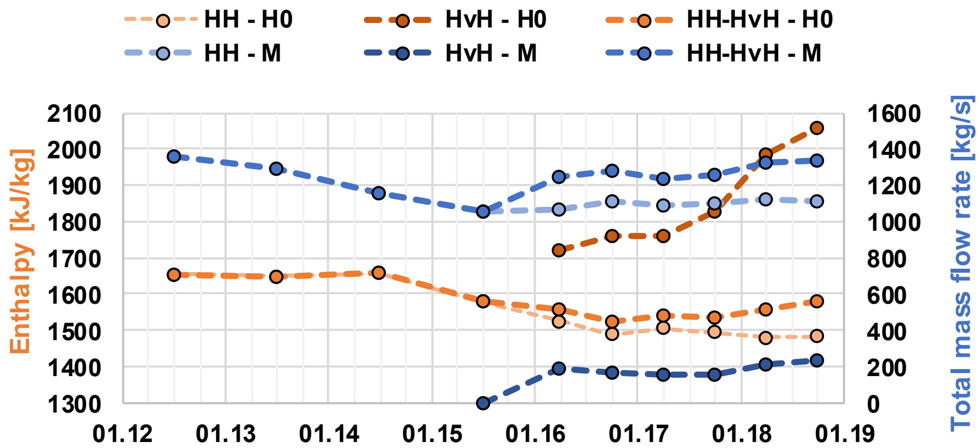


Figure 4: Maximum production capacity at Hellisheiði Power Plant from 2012 to 2018. Blue dotted lines represent changes in total mass flow rate (M, kg/s), calculated from levelized wellhead pressure and productivity curves for each time. Orange dotted lines represent changes in enthalpy, weighted average (H0, kJ/kg). HH and HvH denote the two steam gathering systems for Hellisheiði Power Plant and HH-HvH denotes the combined system.

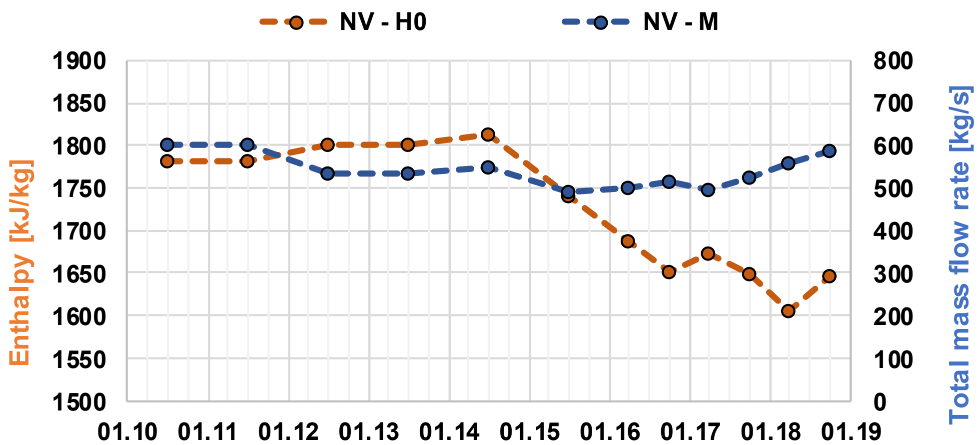


Figure 5: Maximum production capacity at Nesjavellir Power Plant from 2010 to 2018. Blue dotted lines represent changes in total mass flow rate (M, kg/s), calculated from levelized wellhead pressure and productivity curves for each time. Orange dotted lines represent changes in enthalpy, weighted average (H0, kJ/kg).

2.2. Numerical modeling

A numerical model has been developed of the entire Hengill Area using the TOUGH2/iTOUGH2 software suit (Pruess et al. ,2012 and 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. Figure 6 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 (Gunnarsson, G. et al., *this issue)*.

The model is calibrated using initial pressure and formation temperature profiles of wells, and production history such as 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 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.

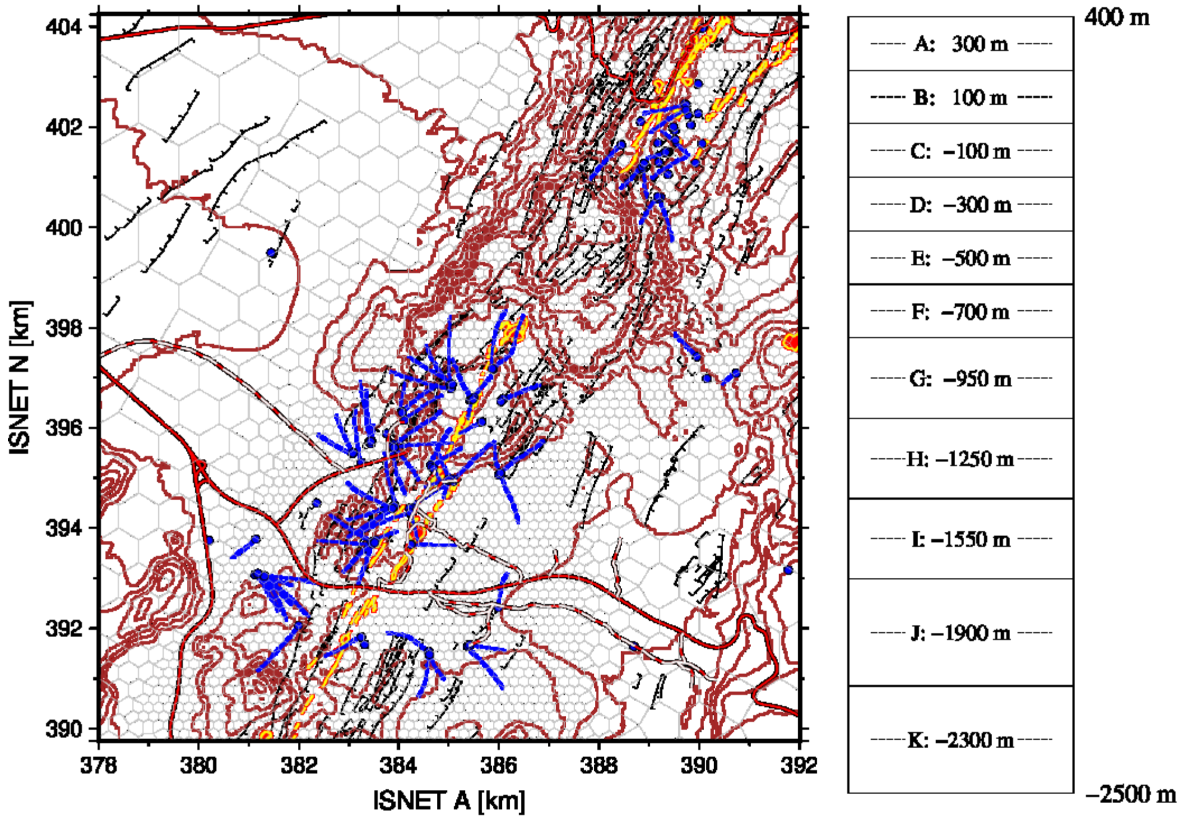


Figure 6: The elements in the center of the numerical model of the Hengill Area and the layering structure of the model. The grid is mainly hexagonal having finer element size in the center (Gunnarsson et al., *this issue*).

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 (Gunnarsson et al., *this issue)*. According to the results of a calibrated model, the annual decline in power generation capacity has been estimated to be around 3% in both fields.

4. SUMMARY AND CONCLUSIONS

There are two different methods used to monitor changes in production capacity for Hellisheiði and Nesjavellir Power Plants. Both methods rely on production data such as pressure monitoring and changes in enthalpy of extracted fluid. One method uses linear regression method between two data-points for each production well to estimate the decline in production capacity, making the summation for all wells the total change in production capacity. The other method uses a calibrated numerical model of each geothermal system to forecast the decline in production capacity, assuming there are no make-up wells drilled to maintain full production.

The results from the two methods are independent of one another and show similar results, approximately 3% annual decline in production capacity. Both methods are taken into consideration as the total change in production capacity is updated, considering the uncertainties and simplifying the results for clarification. The information on changes in production capacity are updated once or twice a year, often being small changes from each update. Both methods are still under development. The former method is being expanded to make use of more than two data-point for each well whereas the latter method is being updated with more monitoring and production data.

Knowing the changes in production capacity is of great importance when it comes to decision making such as maintaining production capacity by drilling make-up wells, planning to reduce production with declining capacity and more. The economic feasibility of both Hellisheiði and Nesjavellir Power Plants is monitored and updated with new data on the changes in capacity (Gunnarsson, G., et al., *this issue)*. The estimation of changes in production capacity is also vital when planning the quantity and location of production and re-injection (Gunnarsson, I., et al., *this issue*), making the monitoring of changes in production capacity one of the most vital indices for a geothermal system.

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