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APPLYING THE HENGILL GEOTHERMAL RESERVOIR MODEL IN POWER PLANT DECISION MAKING AND ENVIRONMENTAL IMPACT STUDIES

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ABSTRACT

Growth in geothermal power production in the Hengill area of Iceland, and a need for environmental impact studies that look hundreds of years ahead, has resulted in new challenges for numerical model developers. An existing, large-scale, iTOUGH2-based 3-D reservoir model of the Hengill volcano has recently been recalibrated and used to study the impact of 400 MWe and 700 MWt cogenerations in two subareas of Hengill, Hellisheidi, and Nesjavellir. Reservoir performance is predicted for the next 30 years, followed by 1,000 years of recovery. The study indicates that the Hellisheidi subfield has greater growth potential than Nesjavellir. Increased production in Nesjavellir results in considerable pressure interference and reduced output of the average well. A plan to expand power generation from 120 to 150 MWe has therefore been put aside because of the cost; new discoveries in the conceptual reservoir model or increased coverage of the wellfield may revive the plan. The Hellisheidi power plant, on the other hand, may still sustain a production load increase from the already-decided-on 150 MWe to 270 MWe. The growth potential arises from a wellfield expansion to the north, in an area without wells and no forced model production. At the end of the generation period, model pressures revert to natural state levels over roughly the same time as generation has taken place, 50–60 years. This behavior is a result of the open boundaries of the reservoir model. The heat reserve requires up to 1,000 years for recovery. Large geothermal power plants in Hengill appear to produce at rates exceeding natural recharge. To make the power generation renewable, either resting periods are required or production must later be reduced to boundary recharge rates. These power plants should, nevertheless, qualify as sustainable development because of the technical and scientific advancements that accompany these intense field activities. To achieve this goal, all relevant field data and scientific publications must be documented and made open to the public.

INTRODUCTION

The vast geothermal system of the Hengill volcano in southwestern Iceland is a potential resource for meeting the electrical and heating needs of Reykjavik, surrounding areas, and industries within Iceland (Figure 1). Reykjavik Energy is currently operating 120 MW electric (MWe) and 300 MW thermal (MWt) power plant units in the Nesjavellir field. Another 95 MWe electrical unit is to be commissioned in the Hellisheidi area in September 2006. A decision has been made to expand this plant to 270 MWe and 400 MWt in 2008–2009. For this endeavor, 45 deep production wells have already been drilled around Hengill, yielding on the average 5 MWe and 60 MWt per well. In addition to the current development, a study is under way to address the feasibility of installing an additional 200 MWe in 2010, taking the total power generation out of Hengill up to 600 MWe.

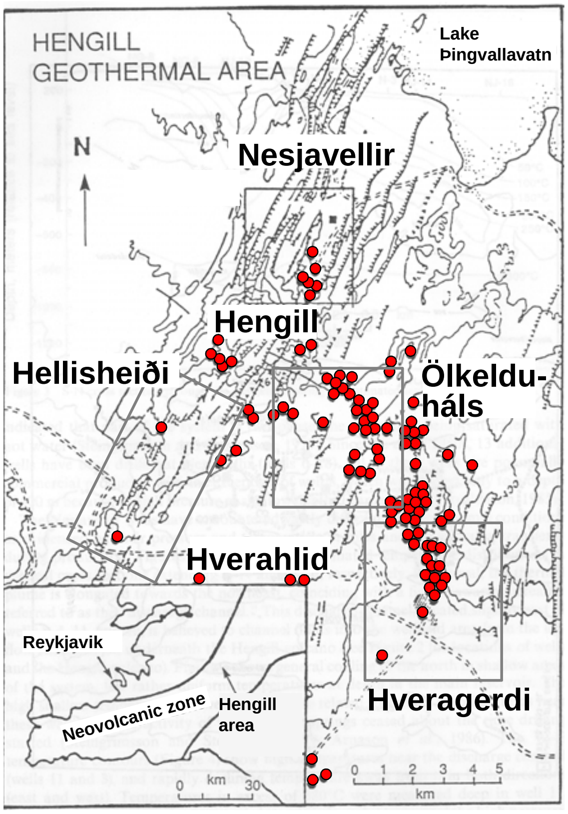

Figure 1. Location of the Hengill central volcano and the Nesjavellir, Hellisheidi, Hveragerdi, Ölkelduhals and Hverahlid subfields. Hot springs and fumaroles are shown by bullets (•) and major faults by tagged lines (from Bodvarsson et al., 1990).

Several subfields have been defined within the greater Hengill area, based on the geology and chemistry of fumaroles (Figure 1). These are: *Nesjavellir*, where the 120 MWe power plant is currently in operation; *Hellisheidi*, where 270 MWe will come on-line in 2008; *Hveragerdi*, where the geothermal resource is utilized by the local community; *Ölkelduhals*, a location of intense seismic and surface activity, where there are two production wells (with one more drilled this year), and finally *Hverahlid*, with one existing production well and two more drilled this year.

The current activities in the greater Hengill area require considerable multidisciplinary effort across the geothermal sciences and engineering, including surface mapping, drilling, resource assessment, modeling, marketing, construction, and finally management of power plants, wells and subsurface resources. For these processes, numerous permits and licenses are being requested by various local and national regulatory authorities. Among these, environmental impact assessment studies are likely the most challenging—not only for the field developer but also for the National Planning Agency (NPA), who reviews environmental impact reports and issues important permits for new power plants. Their task is far from straightforward; in particular when it comes to estimating the impact of a project for hundred of years (as opposed to the conventional 20–30 years needed to pay back the cost of new power plants). As a result of this situation, an existing numerical model of the Hengill area reservoir has often been used to study the feasibility of new power projects, while also assessing the very-long-term response of the geothermal resource to production. That work is the subject of this paper.

In this paper, we first present a conceptual model of the Hengill area reservoir. The 20-year history of numerical model development at Nesjavellir and Hengill is described, and the current numerical model is also briefly addressed. The recalibration phase of the Nesjavellir portion of the model is shown, and the feasibility of expanding the power plant at that site is discussed. New developments in the Hellisheidi area are also covered, in particular how the reservoir model has assisted in the decision-making process. We then describe our approach to estimating recovery times for heat and mass reserves in Hengill, assuming that all power generation will terminate in 2035. This is to better determine whether the impact of planned power-generation scenarios is reversible. Computed changes in mass and heat reserves are shown, and pressure interference from new production fields to the current ones is estimated by the numerical model. The paper concludes with a discussion on the benefits received from the numerical model, both in decision making by Reykjavik Energy and in assisting environmental authorities with their work.

THE CONCEPTUAL MODEL

The Hengill volcanic system lies on the boundary between the North American and European plates. The 2 cm/year rifting of the two plates activates a NNE trending system of normal faults and frequent magma intrusions. The rift zone is permeable, with numerous fumaroles and hot springs on the surface. This system is currently active, whereas its predecessor, the Hveragerdi system, is volcanically extinct but still hosting geothermal resources. Geology, geophysics, and drilling indicate a total resource area of around 110 km^2 (Gunnlaugsson and Gislason, 2005).

The bedrock in the Hengill area is composed of basaltic lava layers, thick sequences of hyaloclastites, and vertical intrusions. Two NNE-striking volcanic fissures, which intersected the Hengill volcano 2,000 and 5,500 years ago, act as primary conduits for subsurface fluid flow in both Hellisheidi and Nesjavellir. Normal faulting is extensive and strikes to the NNE, leaving behind a fractured 3–4 km wide graben that has proven highly productive when drilled. Other fault directions are evident—both N-S, as in the S-Iceland seismic zone, and also transverse E-W (Tang et al., 2006; Tryggvason et al., 2002). Reservoir fluid is 240-330°C fresh water, low in total dissolved solutes (TDS) and gas. The geothermal reservoirs are liquid dominated and commonly sit on the boiling-point-with-depth profile.

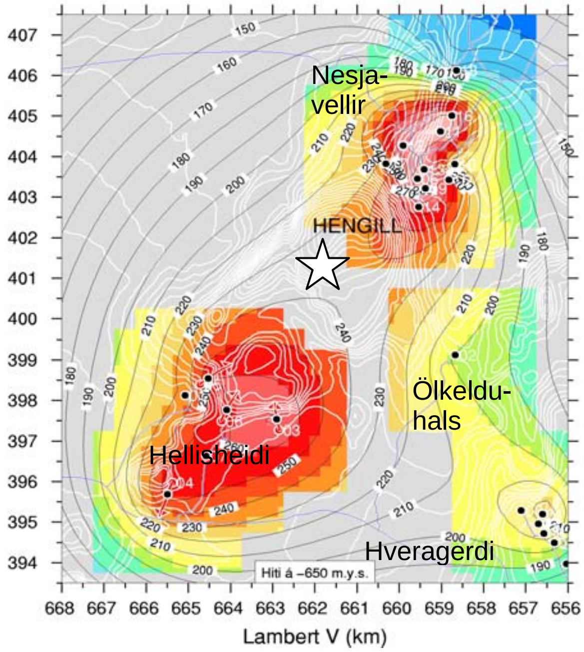

Figure 2. Temperature distribution (°C) at 650 m b.sl. in Hengill. Star shows upflow zone for Hellisheidi and Nesjavellir. Black dots are wells.

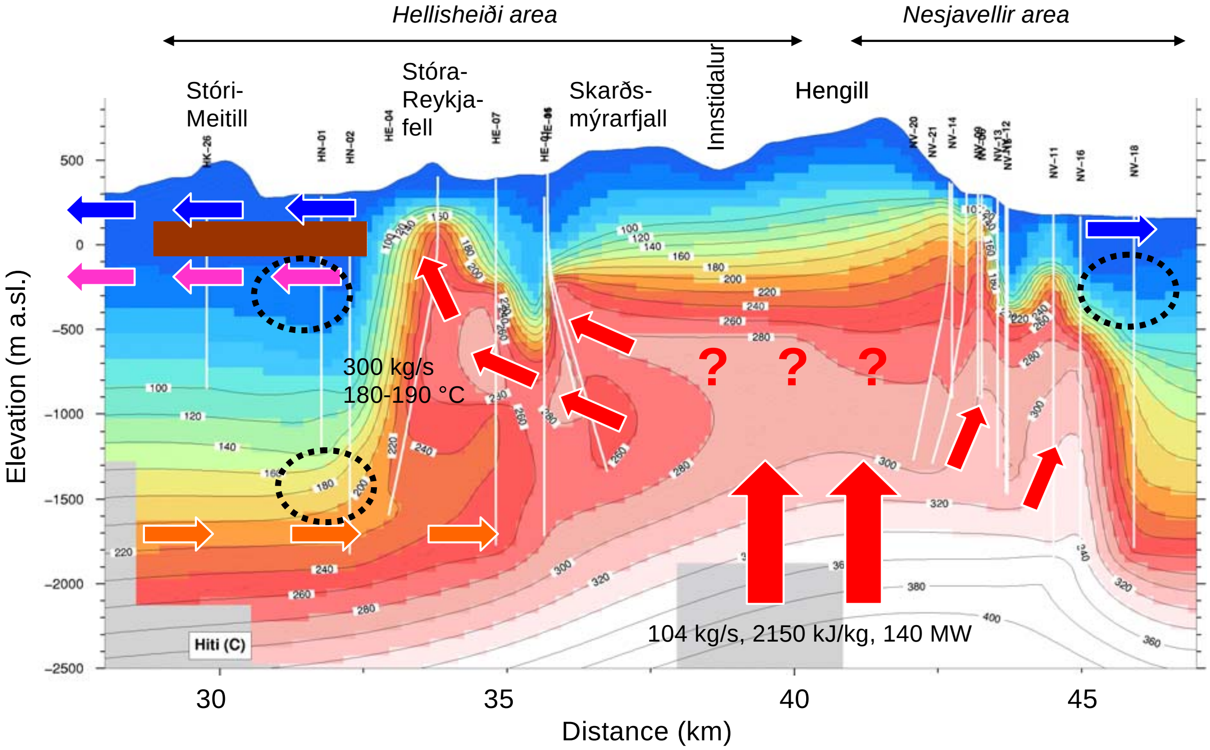

Figure 3. A S-N temperature cross section between Hellisheidi and Nesjavellir. Arrows denote direction of flow. Cross section location is from lower left to upper right corner of Figure 2. Ellipses show re-injection sites.

Figure 2 presents measured temperatures at 650 m below sea level in the Hengill area. One dominant feature is the elongated temperature high (>240 °C) between the Hellisheidi and Nesjavellir fields. A common upflow zone for both fields is suggested near the Hengill summit.

Figure 3 presents a temperature cross section drawn between the Hellisheidi and Nesjavellir subfields of the Hengill system. The conceptual reservoir model is based on the figure. An upflow zone of hot fluid resides beneath the summit of the Hengill volcano. The ascending fluid then flows diagonally or laterally into both the Nesjavellir and the Hellisheidi fields. A gradual rise in temperature is observed with depth in Nesjavellir, whereas temperatures are reversed at Hellisheidi, a reversal explained by a lateral, cooler fluid recharge from the south. One driving force for the deep recharge is presumed to be a pressure low within the high-enthalpy upflow zone, at >2 km depth. Cold groundwater reservoirs are fed by rain and snowfall on the Hengill topographic high. These discharge tens of cubic meters of cold water into Þingvallavatn Lake in the north and to the coastline in the south. Drilling of re-injection wells south of Hellisheidi have identified an interbedded warm outflow zone, most likely resulting from mixing of deep and shallow fluids. Re-injection from the Hellisheidi Power Plant will take place within this zone and also at greater depths within the active rift zone. The Nesjavellir plant reinjects separated fluids at intermediate depths, but not into the deep resource.

A major seismic episode struck the Hengill area between 1994 and 2000, resulting in more than 80 thousand quakes (Vogfjord, 2005). Geodetic surveys confirmed up to 2 cm/year vertical crust movements that have been attributed to a minor inflation of a magma chamber in the Ölkeduhals area (Sigmundsson et al., 1997). Altogether, these geological and geophysical data point towards a dynamic geothermal resource of a large scale.

NUMERICAL MODEL DEVELOPMENT

Numerical modeling of the reservoir has been considered an integral part of the Hengill Wellfields development and management strategy. Table 1 gives an overview of milestones in the model history. The Nesjavellir subfield was initially modeled in 1986–1988 (Bodvarsson et al., 1990 a, b). The model has been expanded and recalibrated several times as more production and drilling data has become available (Bodvarsson, 1993; Bodvarsson 1998; Bjornsson et al., 2000). This effort is considered a success: the model has repeatably been able to forecast field response to production. One positive feature in the Nesjavellir field response to the long generation period is that the outer model boundaries are more permeable than initially anticipated.

Our last English paper on the Hengill numerical model was presented at the TOUGH2 symposium in 2003 (Bjornsson et al., 2003). At that time Reykjavik Energy was addressing the feasibility of building the 120 MWe Hellisheidi power plant, with the first 95 Mwe stage to be commissioned in September 2006. The model was not yet fully calibrated at the time of this conference, resulting in both wet and dry calibrations. But other factors, such as the fact that essential field data are still being gathered in new wells, have also delayed us. Finally, we learned only after the 2003 TOUGH Symposium that environmental impact studies required input from the model.

The final 2003 calibration version of the Hengill model was presented a few months later in an Icelandic report (Bjornsson and Hjartarson, 2003). The model not only considered reservoir performance during 20–30 years of production, but also addressed the recovery times of mass and heat reserves if production were stopped in 2035. Many new features were applied in the model development, the most important of which is that calibration was performed in the inverse iTOUGH2 environment (Finsterle, 1999). Three major advantages follow this approach (compared to the traditional forward modeling by TOUGH2). First, the model had to address a critical question posed by the field owner: Can a power plant in Hellisheidi drain pressure and, hence, affect power generation in Nesjavellir? To provide an answer here, the model had to be large, with the capacity to incorporate data from all subfields of the greater Hengill area. This resulted in a model area of 100 × 100 km (Figure 4).

Table 1. Milestones in Hengill reservoir model development

Year	Model	Generating capacity	Comment
1988	Tough2, 4 layers, 300 elements, 12 x 12 km	300 or 400 MWt	1st thermal unit in Nesjavellir
1992	Same, extended to 100x100 km	400 MWt	Better pressure support
1998	Same, wellfield modifications	60 MWe 200 MWt	2nd Nesjav. unit on line in 1999
2000	Same, minor changes, iTough2	90 MWe 300 MWt	3rd Nesjav. unit on line in 2001
2003	Large scale 3-D, iTough2, cluster	240 MWe 700 MWt	4th unit in Nesjav. New plant Hellish.
2005	Nesjavellir 30 MWe expansion	270 MWe 700 MWt	5th unit in Nesjav. rejected
2005	Hellisheidi 150 MWe expansion	400 MWe 700 MWt	Double plant size in Hellisheidi

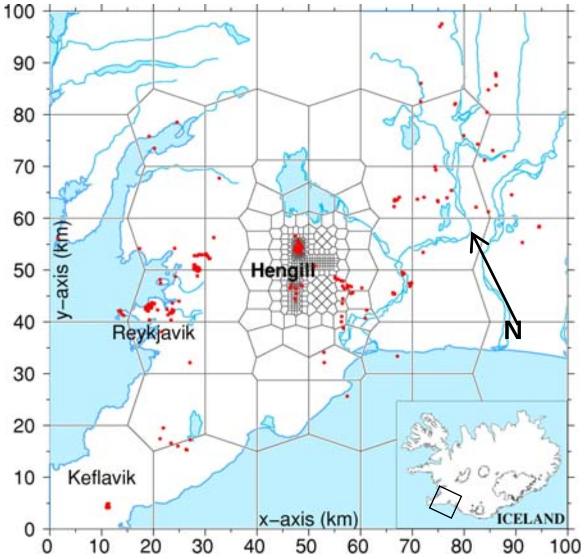

Figure 4. Layout of the Hengill mesh, in model coordinates. Red dots represent wells. The inlet shows mesh location in SW-Iceland.

Second, all field data to be simulated had to be safely and conveniently stored by the input file structure of iTOUGH2. Third, and most important, the automated calibration feature of iTOUGH2 had to save weeks of computation time (and frustration), while at the same time providing clues and suggestions regarding the correlation of parameters and the impact of individual datasets on the objectivity function, which measures the misfit between computed and measured values.

A few other features of the 2003 model version should be mentioned before describing the most recent work:

- Multi-node Linux clusters were applied for parallel computing. They greatly reduced calibration time, measured in working days.
- Model mesh is generated with the AMESH code (Haukwa, 1999). It consists of eight identical layers, with top and base layers inactive. Total number of elements is ~4,300. This approach ensures that the model mesh can be refined in areas of new field data without rebuilding from scratch.
- All wells produce against deliverability.
- Unix scripts were developed, virtually on the fly, for graphics, maintenance, and manipulating input and output files of the iTOUGH2 code. Generic Mapping Tool software (GMT) was used for illustrations (Wessel and Smith, 1995).
- The *steady-state-save* feature of iTOUGH2 proved essential for secure and complete calibration of all field data in one and the same model execution. We even took two additional

measures in time-stepping management. First, a “TIMES” block for model predictions was included in the inverse file. Then, another “TIMES” block was introduced for model recovery computations after 2035. This means that in one and the same execution, iTOUGH2 simulates natural state conditions and known production history, and then computes a future power-generation scenario and model recovery after termination of all power generation. The sacrifice of added computer time (as opposed to breaking down input files for each step separately) is irrelevant compared to the comfort of knowing that future generation scenarios are all based on the same “best model” input files.

- Outer model boundaries were specified at a constant 100°C/km thermal gradient and constant hydrostatic pressure. Only 1 upflow zone is present underneath the Hengill volcano. Temperature reversal in Hellisheidi was imposed by adding mass sinks at the southern margin of the wellfield. (See Figure 3 for source and sink flowrates and enthalpies.)

RECALIBRATION OF NESJAVELLIR FIELD

The 2003 version of the Hengill model is still very much alive and has been activated recently in two projects (Table 1). In one of them, Reykjavik Energy wanted to estimate the response of adding a new 30 MWe unit to the already 120 MWe installed at Nesjavellir (Bjornsson and Hjartarson, 2005). For this purpose, all new field data between 2002 and 2005 were incorporated in the model, in particular pressure drawdown data. These lessons were learned during the calibration process:

- After incorporating all new field data, inverse modeling was applied for calibrating internal properties of the Nesjavellir wellfield. Unlike in the 2003 model calibration, we decided to strictly limit allowed ranges in permeability. This resulted in a permeability range generally narrower than one order of magnitude, compared to the 4–5 orders of magnitude range in the 2003 model.
- We also decided to have a triangular shape of allowed permeabilities, viewed in a cross section perpendicular to the Hengill fissure zone. The highest range complies with the axis of maximum rifting. Lowest permeabilities are specified on the margins of the rift zone. This approach resulted in wellfield permeabilities typically between 20 and 60 mD, near-field permeability between 5 and 15 mD, and far-field permeability from 1 and 10 mD.
- Contrary to the 2003 model, model properties outside wellfields were not inverted in the 2005 calibration, because of the lack of field data to support inverse calibration. Instead, we fixed a 5 mD horizontal permeability at the outer margins and a 0.5 mD in the vertical direction. The anisotropy was necessary for preventing vertical convection in these outer areas.
- Inside Nesjavellir wellfield, the number of model properties was successfully reduced without sacrificing the close match to field data. This accounts primarily for anisotropy in permeability. Most rocks are now isotropic. Permeability barriers, introduced in earlier work, are (for example) nearly nonexistent in the current model.
- Finally, at the end of automated inverse modeling, boundary permeabilities were fine-tuned by forward runs only. This approach provided additional insight into the model behavior under calibration, and was quite efficient. For example, when a 2–3-times-faster host replaced the older one in the Linux cluster, the time for one forward run was reduced to less than 15 minutes.

Unlike in previous model studies at Hengill, recalibration and increased mass production resulted in considerable pressure interference and reduction in mean output at the Nesjavellir wells (Figure 5). The primary reason for this behavior has to do with the limited surface area available for wellpads. The extent of the Nesjavellir wellfield is, for example, severely constrained by the steep hills of Hengill Mountain in the south, towards the upflow zone (Figure 2). According to the model, sufficient steam can be produced out of the reservoir for the 30 MWe expansion. Drilling costs will, however, be high, because the addition must pay down the cost of drilling both new wells and drilling more make-up wells than needed for the 120 MWe power generation. The model study, however, suggests that this conclusion should be revisited if new discoveries are made in the conceptual reservoir model—for example, if a shallow stream zone layer is confirmed by drilling.

Figure 6 compares computed and measured pressure drawdown in observation well NJ-18 in Nesjavellir. Both 2003 and 2005 calibrations are shown. The figure demonstrates the convenience of the iTOUGH2 environment. Only 2–3 lines of new field data had to be added to an existing inverse input file to update this well from the 2003 to the 2005 model.

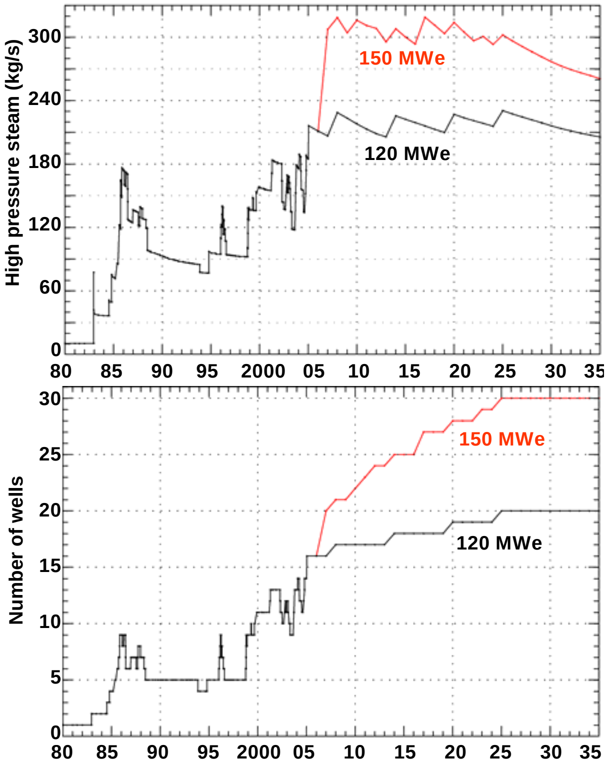

Figure 5. High-pressure steam flow and number of flowing wells in the Nesjavellir 120 and 150 MWe scenarios. Model calibration from 2005.

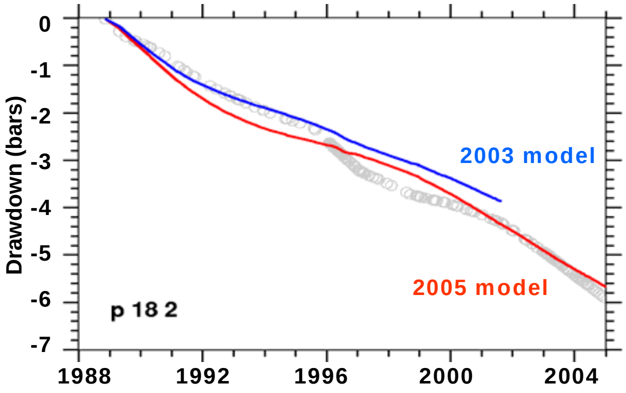

Figure 6. Computed (lines) and measured (dots) pressure drawdown in well NJ-18 in Nesjavellir. Year 2003 and 2005 models.

Figure 7 shows computed and measured enthalpy and mass flow out of well NJ-11 in Nesjavellir. This well is sensitive to discharge and shut-in of wells in the vicinity, resulting in variations in the well output. The 2003 model matched the production data quite nicely, whereas the 2005 calibration is less able to match the high enthalpy periods.

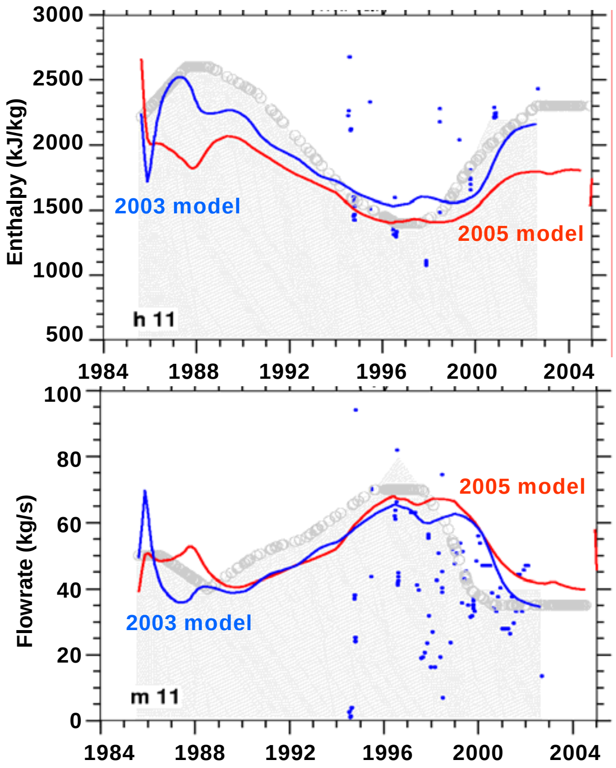

Figure 7. Computed (lines) and measured (dots) flowrate and enthalpy of well NJ-11 in Nesjavellir. 2003 and 2005 models.

The 2005 model enthalpy mismatch in Figure 7 might be fixed by adding layers to the model. However, we chose not to do this, because of the large areal extent of the model and the identical layering throughout the domain. Alternatively, a permeability barrier to the west of NJ-11 can be made tighter, thereby reducing pressure support to the well and increasing boiling. Such small modifications in local model properties can, however, cause undesirable chain reactions in data matching in many other wells. We therefore prefer to hand this kind of situation to the automated inverse part of iTOUGH2, where all data sets contribute to optimum matching.

ENVIROMENTAL IMPACT ASSESMENT FOR THE 120 MW HELLISHEIDI POWER PLANT

The electricity market in Iceland is currently favorable for power producers, because the local aluminum industry has expanded. Since there is growing concern about the environmental impact of large hydropower projects, both the energy-intensive aluminum industry and the national political climate strongly favor new geothermal projects. Reykjavik Energy, which has become one of the players in this market situation, will commission the first stage of the Hellisheidi power plant next September. This unit passed the environmental licensing process in

February 2004, and a power purchase agreement was signed a month later.

The National Planning Agency (NPA) notified Reykjavik Energy back in 2003 that the traditional 20–30 years of reservoir performance studies provided by numerical modeling are insufficient for their licensing process. Field operators should recognize that many generations to come will harness heat and mass resources in Icelandic geothermal areas. Environmental impact reports therefore must look much farther ahead than bankers do, in order to respect goals set by sustainable development and renewable energy policies. This message placed reservoir modelers in an unusual situation. As an example, reservoir performance in the Hellisheidi area was based on limited well and production data. These data were hardly sufficient in 2003 to predict with confidence reservoir performance over 20–30 years of massive power generation, not to mention several hundred years. Browsing through the geothermal literature did not either provide any examples to follow, and we therefore decided to focus on the following:

- Admit that the science of geothermal reservoir engineering is still developing; meaning that model predictions may change as more is learned.
- Emphasize that in the current numerical model, uncertainties are interpreted conservatively. As an example, the model base layer is set tight at 2 km below sea level (Figure 3). The upflow zone recharge rate also stays constant in the model, despite a computed pressure drawdown. Events in geological history, like frequent magma intrusions, are excluded. Finally, the drilling history at Hellisheidi has shown that temperature reversals in many wells are less severe than indicated, by 6–12 months of thermal recovery after drilling. It is expected that these combined uncertainties indicate that the numerical model underestimates heat and mass reserves at Hengill, while overestimating the impact of generation. The model study therefore respects a rule of thumb applied in Iceland and elsewhere, that uncertainties are interpreted in favor of nature, not the power project.
- Generate geothermal fluids out of the model, at full load, up to 2035, and then terminate production. Compute heat and mass in storage between 1975 and 2035 and also during 3,000 years of recovery. Observe whether these two resources are recoverable and at what rate. The idea here is that although there is limited power-generation history available for 20–30 reservoir performance studies, the numerical model should be suitably constrained for the recovery estimation. The steady-state field data should ensure this.

Figure 8 shows the history of model pressure and temperature at several locations within the Hengill area. Two features are of interest here. First, the model pressure will recover to initial values over roughly the same time as production has been ongoing, 50–60 years. In that sense, we conclude that the mass reserve at Hengill could be rather easily recovered.

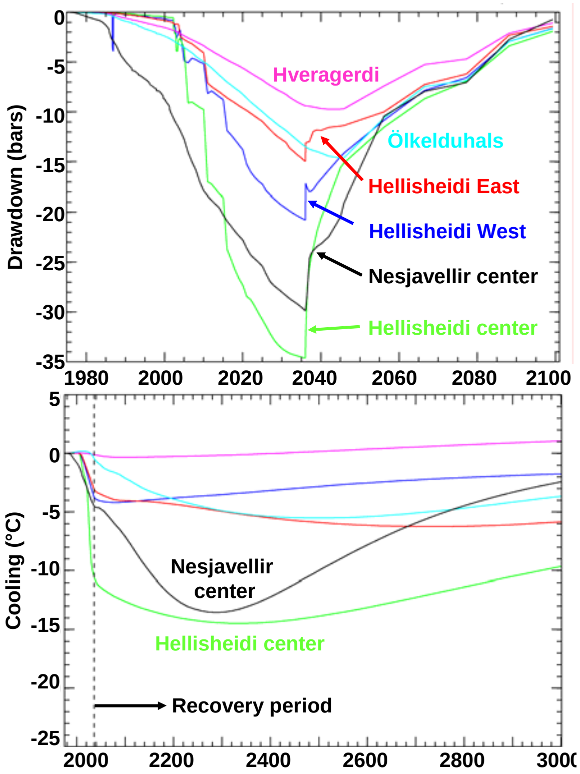

Figure 8. Computed temperature and pressure changes at several locations in the Hengill model, during production and recovery. Based on 2003 model calibration.

On the other hand, the model temperatures in Figure 8 need considerably longer time to recover than the pressure, nearly 1,000 years. Interestingly, we compute continuation of cooling trends after power generation is stopped. This may have to do with condensation of boiling volumes and the fact that cooler boundary recharge shows up faster within wellfields than mass and heat coming from the constant rate upflow zone. However, that recharge will eventually take over and bring the model back to the pre-exploitation status of 1975.

Although the in-field cooling of 10-15°C in Figure 8 seems considerable, note that the resource initial temperature is 250–320°C. This predicted temperature loss is still within the limits needed to keep wells flowing at pressures above that of the steam gathering system. Loss of producing wells in 2035 is therefore not anticipated, meaning that the resource will keep producing for the benefit of more generations to come. That should allow the project to qualify as sustainable. Power-generation rates will, however, exceed recharge rates. The planned generation rates are therefore nonrenewable and may need to be reduced in the future back to rates equal to the boundary recharge. Such a long-term production scenario has, for example, been proposed by Lovekin (2002). Alternatively, one can envisage that old power plants will be dismantled and resting periods will last, for example 1-2 generations. This can easily happen, especially if the geothermal power industry fails in supporting continuous development of exploration sciences, production and drilling techniques.

Thankfully, this appears not to be case in Iceland at present. Recently, the government, together with 3 power companies and scientific foundations, has committed themselves to finance and drill up to 5 km deep wells, to tap supercritical reservoirs (Elders et al., 2005). Despite a high risk of failure, the project may optimally show that geothermal convection cells penetrate much deeper into the crust than presumed in the current resource assessment. If true, the size of thermal and fluid reserves in Hengill may triple to fivefold, not to mention the high efficiency of supercritical fluids in power plants. We therefore anticipate that the maximum power-generation potential of the Hengill resource can be raised towards a sustainable limit criterion, defined (for example) by Axelsson et al. (2005).

But there are other factors that contribute to our conclusion that intense power production in Hengill area can comply with goals of sustainable development. Reykjavik Energy has, for example, a policy to keep field data and reports open to the public, meaning that lessons learned will pass on to the future, for the benefit of more generations to come.

ENVIROMENTAL IMPACT ASSESMENT FOR A 270 MWe HELLISHEIDI POWER PLANT

The reservoir model that was calibrated in 2003 is among several base studies that Reykjavik Energy (and the National Planning Agency) used to license and decide on building the first unit of the 120 MWe and 400 MWt Hellisheidi power plant. Drilling has been ongoing between 2003 and 2005, and steam for the first 95 MWe stage is already secured. A decision was made in 2003 to drill directional wells, where many cross a 5,000 year old volcanic fissure in the area, and this drilling was carried out successfully. Wells are made to discharge before fully recovering thermally. A gradual rise in enthalpy is commonly observed during the first 2–3 months of flow, when equilibrium is finally attained. This behavior strongly suggests matrix-dominated flow instead of the more common fracture-dominated flow, as in Nesjavellir. Pressure drawdown in Hellisheidi is also minimal during a several-month flow testing.

Because of the positive results in the Hellisheidi project, and the demand for more electricity, Reykjavik Energy decided to continue with this power plant development, this time doubling the electrical output to 240 MWe in condensing units and another 30 MWe in a second flash unit. An Environmental Impact Report was submitted to the NPA in December 2005, and the project passed their screening in March 2006. In the reservoir study, as in the 2003 model calibration, we decided to put emphasis on sustainable development (Bjornsson, 2005). Steam for the power plant addition is to be tapped from a new wellfield on Skardsmyrarfjall Mountain, a site where drilling is still to take place (Figure 3). Because of the absence of wells, mass generation is simply forced out of this model area until sufficient high-pressure steam is produced for the 120 MWe power plant expansion. This approach of forced production has the disadvantage that a likely number of production and make-up wells is not predicted by the model. Instead, the owner can refer to the 5 MWe statistical average, now confirmed in the existing Hellisheidi wellfield, for preliminary cost estimates.

Figure 9 shows how elements for new production wells in Skardsmyrarfjall Mountain were selected. First, geologists and reservoir engineers explored the new wellfield and selected sites for well pads. A 1,200 m maximum drilling distance circle was drawn around the selected well pads. Forced production was finally distributed to elements inside the cumulative area of influence, excluding the existing wellfield to the south.

With new production elements at hand, the study proceeded into computing the field response to production (Figure 10). As to be expected when production is forced, an enthalpy rise is predicted over time, while steam flow is maintained in excess of 200 kg/s, as required by efficient 120 MWe condensing units.

Although the power generation at Skardsmyrarfjall is very crudely defined in the 2005 version of the numerical model, other wells in Nesjavellir and Hellisheidi still produce against deliverability. The model should therefore be able to estimate pressure interference and, hence, predict a negative impact of the 120 MWe Skardsmyrarfjall expansion on pre-existing power plants. Figure 11 shows this for the 120 MWe units at Nesjavellir and the first 120 MWe unit at Hellisheidi. Negative interference is predicted in the current Hellisheidi area, gradually reducing the total steam flow there by 20% by 2035. The cumulative loss, in tons of steam, is 6%. The opposite behavior is seen in Nesjavellir, where total steam flow increases slightly. This is related to an additional 5 bar pressure drawdown in Nesjavellir that raises the boiling and mean enthalpy of wells and, consequently, total flow of high-pressure steam.

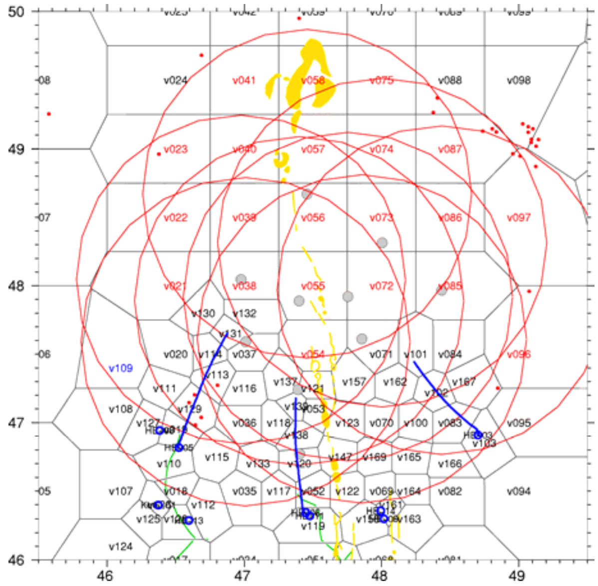

Figure 9. New wellpads on Skardsmyrarfjall Mountain (gray circles), their radius of drilled influence (red circles) and elements to be produced out of a 270 MWe production model (in red letters). Blue lines and dots represent existing wells. Yellow denotes the 2005 volcanic fissure. Model coordinates in km.

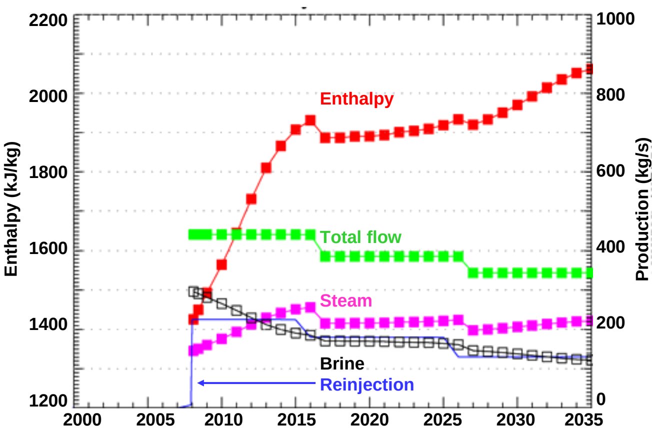

Figure 10. Predicted mean enthalpy and total production out of new wells at Skardsmyrarfjall Mountain. Production is forced.

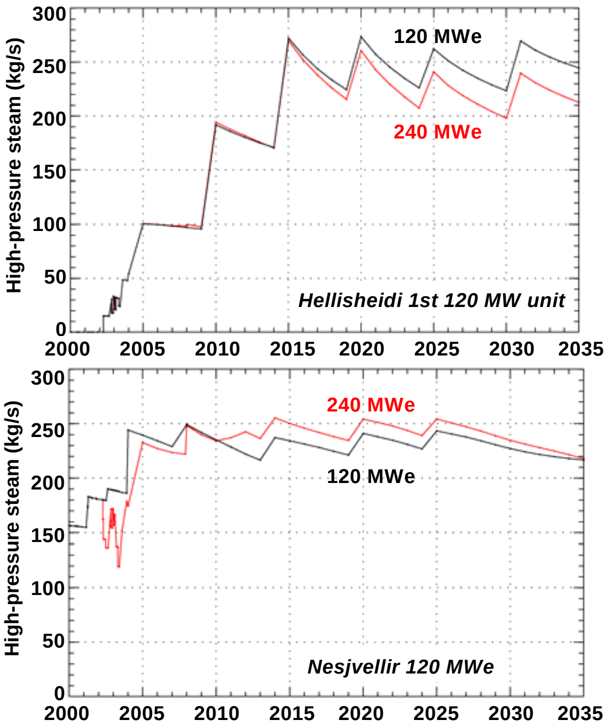

Figure 11. Predicted interference on high-pressure steam flow in Hengill model, with (red) and without (black) the 120 MWe addition to Skardsmyrarfjall Mountain. Upper part is the current Hellisheidi power plant; the lower part shows Nesjavellir performance. Time is year.

Recovery of mass and heat reserves in the complete Hengill numerical model was then predicted like in the 2003 calibration, assuming that all generation will terminate in 2035. Conveniently the TOUGH output file contains total mass and heat reserves in the model at every printed time step. These lines are easily extracted by a simple UNIX command like:

```
grep “THE TIME IS” tough_output_file
```

to yield lines with total heat and mass in the model with time. Changes in these quantities, relative to time zero, are shown in Figure 12. The model heat reserve reaches a minimum near 2035, but has almost fully recovered by 3000 for the 240 MWe version of the 2005 model calibration. The 2003 calibration, on the other hand, already exceeds the initial heat content by 2500 and has gained additional 1 EJ (Exa Joule or 10^{18} J) by 3000. This model behavior is attributed to the length of the *steady-state-save* time step in iTOUGH2 inverse file, meaning that the 2005 model is in better equilibrium at time zero than 2003.

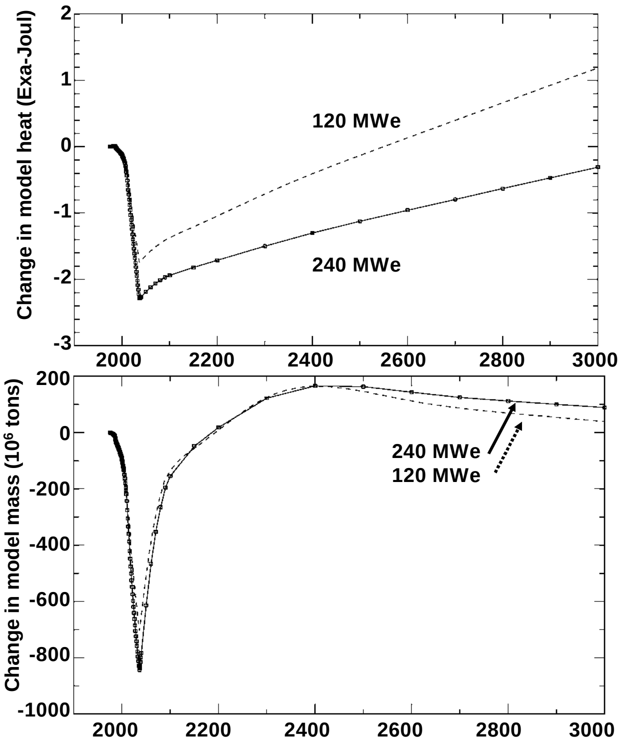

Figure 12. Predicted changes in mass and heat reserves in the Hengill model, relative to time zero in 1975. Solid line refers to 120 MWe addition on Skardsmyrafjall, while the dashed one considers only 120 MWe in Hellisheidi. Nesjavellir generate 120 MWe in both cases.

Analyses like the one in Figure 12 show that despite aggressive production scenarios now considered in the Hengill area, the heat and the mass reserve can be regained by resting production fields. This accounts in particular for the mass reserve, which is replenished by good boundary recharge and will recover over the time that production is ongoing. The 25-year production history in Nesjavellir has confirmed this favorable boundary property. Intense seismic activity is another indicator of high permeability on the large scale. Depletion of mass in storage is therefore of less concern than heat depletion in overall Hengill resource management. Finally, it should be noted that the 2 EJ maximum change in heat reserve (Figure 12) is to be compared with a 3000 EJ total heat content in the model domain.

CONCLUSIONS

The following are major conclusions of this paper:

A large scale, 3-D numerical reservoir model of the Hengill area, presented at the TOUGH symposium in 2003, has continued to assist in decision making and environmental licensing for new power plants in this large volcanic region.

The iTOUGH2 environment, parallel computing on multinode clusters, input and output files processed by Unix/Linux tools and scripts, plus continuous support of this project by Reykjavik Energy—all have contributed to and optimized the modeling effort. Long-term model maintenance has, furthermore, been recognized as a standard and valuable tool in Hengill resource management.

New field data collected in Nesjavellir between 2002 and 2005 have been simulated by the model. The model shows that more steam can be produced in Nesjavellir than needed for the current 120 MWe and 300 MWt plant. Unfortunately the model also predicts substantial pressure interference if production is increased, resulting in reduced mean output from the average well in the field. Drilling costs therefore appear much higher for a 30 MWe addition than for the existing units. This conclusion should be revisited if new discoveries are made in the reservoir conceptual model or if the wellfield can be expanded into the rough topography of Nesjavellir.

The power generation potential of the Hellisheidi field appears much higher than at Nesjavellir, because of Hellisheidi's larger resource area. Current wellfields can sustain cogeneration of 400 MWt, 120 MWe in condensing units and 30 MWe in a second flash unit.

An additional forced generation of 120 MWe in Skardsmyrarfjall—a new, undrilled area in Hellisheidi—results in gentle pressure interference to existing production fields. A 20% loss in high-pressure steam flow is estimated at the end of a 30-year generation period, while the cumulative loss is only 6%. A five-bar pressure interference is predicted in the Nesjavellir field, but, according to the model, this will not affect high-pressure steam flow there. New and make-up wells are not predicted in this case for the Hellisheidi addition.

Termination of 400 MWe and 700 MWt power generations at Hellisheidi and Nesjavellir power plants by 2035 results in fast recovery of the subsurface fluid reserve. Full recovery is obtained over a time period similar to that of production (50–60 years). The heat reserve requires a longer time, but has also fully recovered in 500–1,000 years.

The current plans for mass and heat production in Hengill are considered aggressive and at rates exceeding boundary recharge. A slow down in power-generation rates is to be expected in the future, to make the production renewable. Alternatively, resting periods may become necessary.

The open data and report policy of Reykjavik Energy, its will to comply and work with national and local environmental licensing authorities for optimal resource utilization, and firm plans to explore deeper parts of Icelandic high-temperature resources—all should allow the current Hengill project to qualify as sustainable. Generations to come should therefore benefit from the current activities, owing to the scientific and technical advancements gained.

We expect a fruitful continuation of the Hengill modeling work described in this paper. However, there are still new challenges to face. For example, deep exploration plans may quickly approach temperatures and pressures beyond the critical point. On the other hand, coupling of chemistry and reservoir engineering is possible now with the aid of TOUGHREACT. New discoveries are bound to be made in that research area. Of particular interest is CO_2 degassing of solidifying magma, a possible driving mechanism for creation and evolution of low-permeability caprocks that efficiently surround and protect most Icelandic high-temperature geothermal reservoirs.

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