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SUSTAINABLE USE OF GEOTHERMAL ENERGY

Benedikt Steingrímsson(1), Guðni Axelsson(1) and Valgarður Stefánsson(2)
(1)Iceland GeoSurvey (ISOR), Grensasvegur 9 108 Reykjavik Iceland
(2)IGA-Secretariat, c/o Samorka, Sudurlandsbraut 48, 108 Reykjavik, Iceland
bs@isor.is; gax@isor.is, iga@samorka.is

ABSTRACT

Sustainable development involves meeting the needs of the present without compromising the ability of future generations to meet their own needs. At the core of this issue is the utilization of the various natural resources, including the worlds' energy resources. Geothermal resources have the potential of contributing significantly to sustainable energy use in many parts of the world. The terms renewable and sustainable are often mixed up. The former concerns the nature of a resource while the latter applies to how a resource is utilized. In many cases several decades of experience have shown that by maintaining production below a certain limit a geothermal system reaches a kind of balance that may be maintained for a long time. A definition is reviewed, which argues that sustainable geothermal utilization involves utilization at a rate, which may be maintained for a very long time (100-300 years). Examples are also available where production has been so great that equilibrium was not attained. Such overexploitation mostly occurs because of poor understanding, due to inadequate monitoring, and when many users utilize the same resource without common management. Two case studies are presented where reservoir modelling is used to analyze sustainable management of the corresponding resources. One is a small low-temperature geothermal system in Iceland, where modelling based on long-term monitoring has been employed to estimate the sustainable potential of the system. The second case example involves a high-temperature geothermal system in Iceland, which is utilized for combined production of thermal energy for space heating and electricity for the national grid. Modelling indicates that the current rate of utilization can't be maintained in a sustainable manner for 100-300 years. The impact appears to be reversible, however, and the field may likely be utilized at a reduced rate, in a sustainable manner, following a 30-year period of excessive utilization.

1. INTRODUCTION

The utilization of geothermal energy in the world was limited through the centuries but has grown rapidly during the last hundred years and presently geothermal utilization is found in more than 50 countries. The understanding of this energy source has grown hand in hand with the development. Old primitive ideas on the origin of the heat and the fluid supply of the geothermal resources and its nature based on limited knowledge have been confronted with extensive new data from exploration, drilling and production of numerous geothermal field throughout the world.

Today geothermal energy is recognized as a renewable energy source. Its basis is the heat flux from the interior of the Earth which has been accessible to mankind through hot springs, fumaroles and other surface manifestation. Present utilization is, however, almost entirely by tapping the geothermal resources through boreholes, typically less than 2.5 km deep. The geothermal energy is produced from the wells as hot fluid, either liquid or steam or both. If the resource temperature at 1 km depth is higher than 200°C the geothermal resource is classified as a *high temperature field* but as a *low temperature field* if the temperature at 1 km depth is less than 150°C.

The high temperature geothermal resources are associated with volcanic activity where hot magma bodies in the upper crust supply heat to the geothermal system and fractured and porous igneous rocks supply permeability and storage for the geothermal fluid (liquid and/or steam) at shallow (<3 km) depth. The low temperature fields are, on the other hand, often associated with permeable sedimentary layers at great depth (2-3 km), or hot igneous fractured rocks at intermediate (1-2 km) depth in tectonically active areas. The high temperature fields have mainly been utilized for electricity generation and an installed geothermal capacity of 8900 MW_e was reported at WGC2005 in Turkey in April 2005 (*Bertani, 2005*) summing up to an energy generation of 57000 GWh per year. The low temperature fields on the other hand are utilized to provide hot water for a various uses, the most important being; space heating, fish farming, industrial drying, bathing etc. The direct uses of geothermal in 2005 are estimated to correspond to almost 28000 MW_{th} (*Lund et al., 2005*) more than three times the installed electric power. The energy used per year is about 72000 GW or similar to the electric energy generation. This is due to a much lower load factor for the direct uses compared to the electric power plants that are operated almost all year around.

Sustainability has come into focus regarding human activity concerning the environment and the natural resources (living or dead) of the world. Geothermal resources have the potential of contributing significantly to sustainable energy use in many parts of the world. There exist geothermal systems of various sizes. Ranging in area extent from a few km^2 to a few hundreds of km^2. The production capacity of the systems is therefore quite variable and different systems respond differently to utilization depending on their setting and nature.

Some five years ago the sustainability of geothermal resources was analysed, discussed and defined in several meetings of a specialist group set up at Orkustofnun in Iceland (now divided into Orkustofnun and ISOR). The group was headed by Valgarður Stefansson and Guðni Axelsson who have later published the definitions, findings and the conclusions of the group and other relevant thoughts in several publications (Axelsson et al., 2001, Axelsson and Stefansson, 2003, Axelsson et al., 2005 and Stefansson and Axelsson, 2005).

In this presentation for the Kenya seminar 2005 the sustainable use of geothermal energy resources will be discussed in view of how geothermal systems respond to production. Consequently, the principal factors of sustainable geothermal management will be discussed and relevant examples given of few geothermal systems that have been under exploitation for few decades.

2. DEFINITIONS OF SUSTAINABILITY AND RENEWABILITY.

The concept *sustainable development* is fairly new. It was first put forward in the Brundtland report in 1987 (World Commission on Environment and Development, 1987) and became immediately a very popular concept. In the Brundtland report, sustainable development is defined as *development that meets the needs of the present without compromising the ability of future generations to meet their own needs*. This definition is clearly vague and ambiguous and must be looked at as a political declaration or goal rather than a scientific definition of this concept. Do we know the needs of generations to come? If we reverse the question and look back few generations the answer is probably that our ancestors had little idea of what our needs would be today. It is therefore understandable that the concept of sustainable development has been interpreted differently by different persons. It seems, however, generally accepted that sustainable development is a development or a process that spans a long time compared to economical time constants in project developments.

Axelsson et al. (2001) suggest 100-300 years to be a reasonable time constant for sustainable geothermal development compared to the 20-50 years amortized life span of geothermal power plants and other constructions. They proposed the following definition which has been adopted by the geothermal community in Iceland:

For each geothermal system, and for each mode of production, there exists a certain level of maximum energy production, E_0*, below which it will be possible to maintain constant energy production from* *the system for a very long time (100-300 years). If the production rate is greater than* $\boldsymbol{E_0}$ *it cannot be maintained for this length of time. Geothermal energy production below, or equal to* $\boldsymbol{E_0}$*, is termed* ***sustainable production*** *while production greater than* $\boldsymbol{E_0}$ *is termed* ***excessive production.***

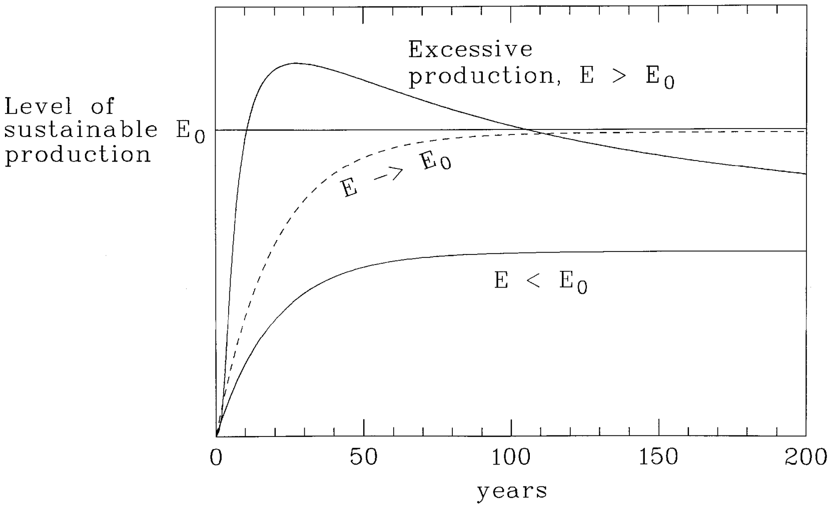

FIGURE 1: A schematic figure illustrating the difference between sustainable and excessive production.

This definition is explained schematically in figure 1. The level of sustainable production, $\mathbf{E_0}$, depends on the nature of the geothermal system in question (size, porosity, temperature, fluid state and saturation and recharge rate) and how the field is operated (artesian flow, pumping, injection, periodic production etc). The definition does not take into account economical or environmental aspects which might change during the life of the development.

It is clear from the definition that a sustainable geothermal resource must be renewable. In the discussions on the nature of geothermal resources the distinction between the concepts renewable and sustainable is, however, often unclear. Our understanding of these concepts is that s*ustainable* depends on how the resource, the geothermal system, responds to utilization and describes to which degree the system is utilized. Is the utilization moderate or is it excessive. The concept *renewable* describes on the other hand the ability of the geothermal resource to replace the energy which is withdrawn from the system. It is therefore a property of the resource. To clarify this Axelsson et al. (2001) proposed the following definition of a renewable energy resource.

The energy extracted from a renewable energy source is always replaced in a natural way by an additional amount of energy and the replacement takes place on a similar time scale as that of the extraction

3. SUSTAINABLE USES

The value of E_0 in the definition of sustainable production is not know prior to utilization but will gradually become known in time when exploration and production data become available. Of special importance are data on how the geothermal resource responds to utilization. Drastic long term changes suggest that the production from the resource is excessive whereas changes which stabilize in time suggest that the production from the field is less than E_0. It is obvious that utilization which is limited to the natural discharge (which is equal to the natural recharge) will be sustainable. Production in excess of the natural recharge does not necessary mean over-exploitation as the natural recharge might increase when reservoir pressures drops due to production. Figure 2 shows such an example for the Laugarnes geothermal field in SW-Iceland, where production was increased by an order of magnitude in the sixties, through the introduction of down-hole pumps (Axelsson and Gunnlaugsson, 2000). This resulted in a reservoir pressure drop corresponding to about 120 m of water level. Production and water level have, however, remained relatively stable during the last three decades. This indicates that the reservoir has found a new semi-equilibrium, with ten times the natural recharge.

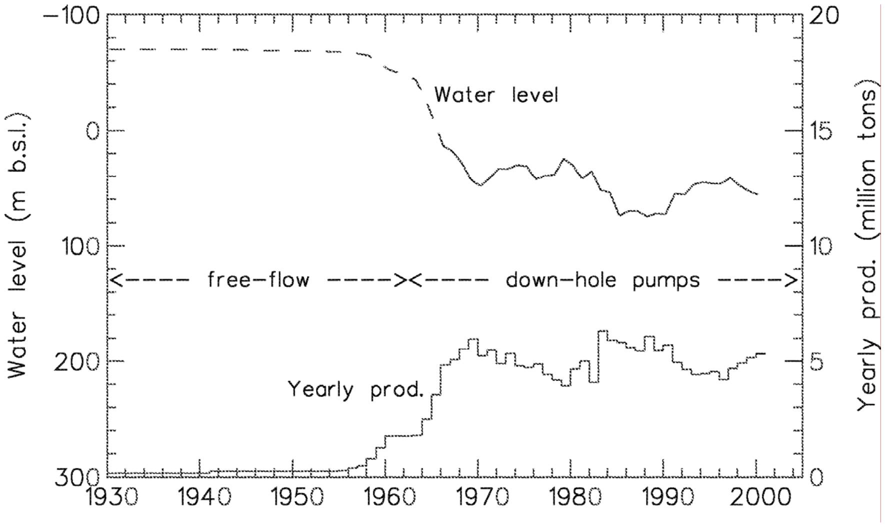

FIGURE 2: Production and water-level history of the Laugarnes geothermal system in Iceland.

An example where production has been so great that equilibrium was not attained is the Geysers geothermal field in California.

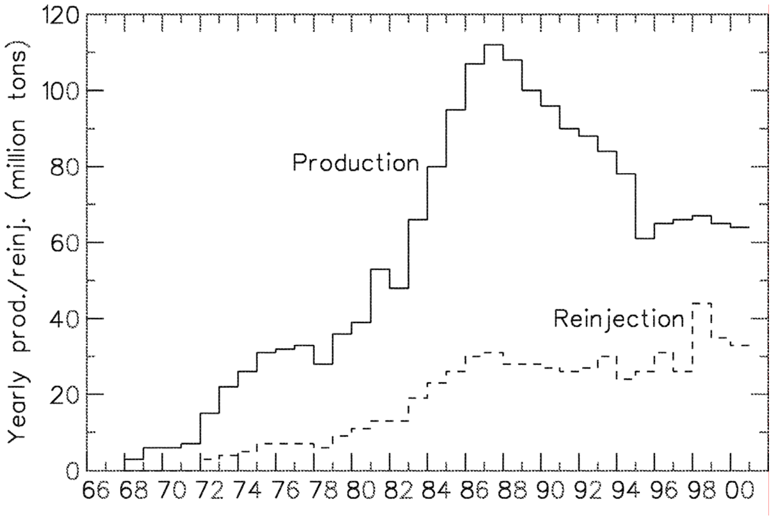

FIGURE 3: Production- and reinjection history of The Geysers geothermal field in California (Barker, 2000).

Twenty geothermal power plants, with a combined capacity of more than 2000 MW_e, were constructed in the field. A drastic pressure drop in the reservoir caused steam production to be insufficient for all these power plants and production declined steadily from 1985 to 1995, as shown in Fig. 3. A relatively stable production has been maintained since 1995, partly through reinjection. The recharge to the Geysers field, therefore, appears to limit the production that can be maintained in the long run.

Even though geothermal resources are normally classified as renewable energy sources, because they are maintained by a continuous energy current, such a classification may be an oversimplification.

Geothermal resources are in essence of a double nature, i.e. a combination of an energy current (through heat convection and conduction) and stored energy. The renewability of these two aspects is quite different as the energy current is steady (fully renewable) while the stored energy is renewed relatively slowly, in particular the part renewed by heat conduction. The semi-equilibrium reached in Laugarnes may reflect the renewability of the corresponding geothermal resources. The renewable component (the energy current) is greater than the recharge to the systems in the natural state, however, because production has induced an additional inflow of mass and energy into the systems (Stefansson, 2000). In the case of Laugarnes it may have increased by a factor of 5-10.

4. CASE STUDIES

The remainder of this paper is devoted to two case studies related to sustainable management but more examples will be mentioned during the lecture in Kenya. One of the case studies is the Hamar low-temperature geothermal system in Central N-Iceland, where modelling based on long-term monitoring has been employed to estimate the sustainable potential of the system. The second study concerns the Nesjavellir high-enthalpy system in SW-Iceland, which is utilized for large-scale thermal- and electrical energy production.

4.1 The Hamar Geothermal Systems N-Iceland

The Hamar geothermal field in Central N-Iceland is one of numerous low-temperature geothermal systems located outside the volcanic zone of the island. The heat-source for the low-temperature activity is believed to be the abnormally hot crust of Iceland, but faults and fractures, which are kept open by continuously ongoing tectonic activity, also play an essential role by providing the channels for the water circulating through the systems and mining the heat (Axelsson and Gunnlaugsson, 2000). This small geothermal system has been utilized for space heating in the near-by town of Dalvik since 1969. Two production wells, with feed-zones between depths of 500 and 800 m, in the basaltic lava-pile, are currently in use and the reservoir temperature is about 65°C. The average yearly production from the Hamar system has varied between 23 and 42 l/s, and the total production during the 33-year utilization history has amounted to 32 million tons. This production has caused a very modest pressure decline of about 3 bar (30 m).

Careful monitoring has been conducted at Hamar during the last two decades and Fig. 4 shows the most significant of these data, the production and water-level data. These data have been simulated by a lumped parameter model, which has been updated regularly, as also shown in the figure. Such models have been successfully used to simulate the pressure response of numerous geothermal systems worldwide (Axelsson and Gunnlaugsson, 2000).

The Hamar system appears to have been utilized in a sustainable manner during the last three decades. The production history is too short, however, to establish whether the current level of utilization is sustainable according to the definition above. Therefore, the sustainable production capacity of the system (E_0 in the definition) has been estimated through modelling. A simple method of modelling was used in which pressure- and temperature changes were treated separately.

The lumped parameter model, already mentioned, was used to predict the pressure (water level) changes in the Hamar geothermal system for a 200-year production history. The results are presented in Fig. 5 for a 40 kg/s long-term average production. The model used is actually a semi-open model where the response is in-between the responses of the extreme cases of a closed system and an open one. It may be mentioned that the two extremes indicate that the uncertainty in the prediction is only about ±30 m at the end of the prediction period. The results also show that the system should be able to sustain more than 40 kg/s, with down-hole pumps at above the current maximum operation depth of 200-300 m.

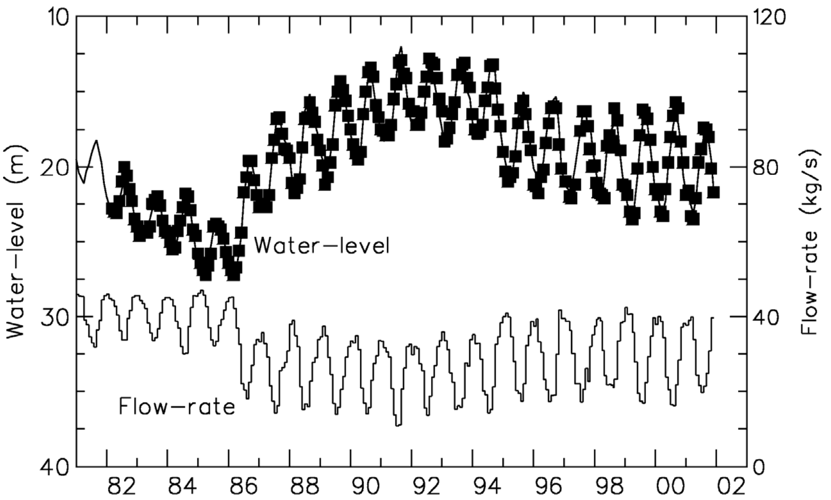

FIGURE 4: Last two decades of the production history of the Hamar geothermal system, the water-level history having been simulated by a lumped-parameter model (squares = measured data, line = simulated data).

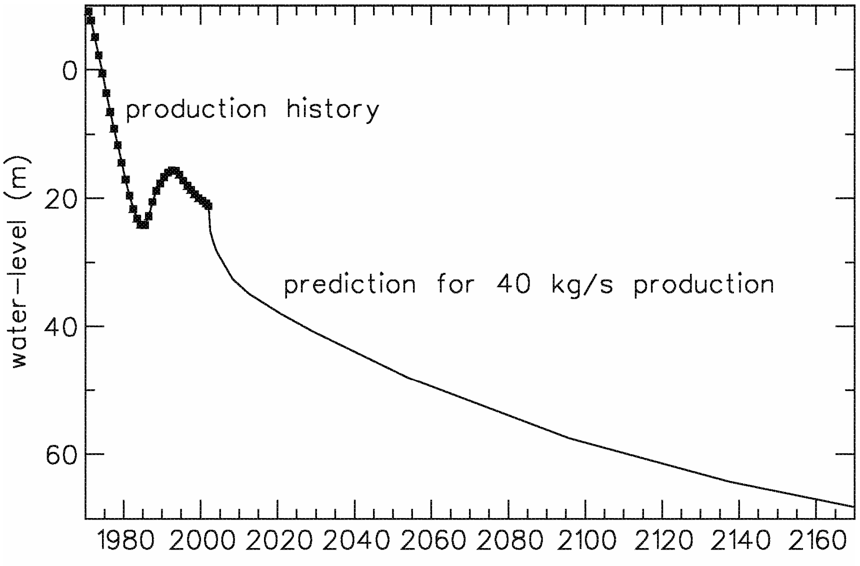

FIGURE 5: Predicted water-level (pressure) changes in the Hamar geothermal system for a 200-year production history.

The eventual temperature draw-down in the Hamar system, due to colder water recharge, is estimated through using a very simple model of a hot cylindrical (or elliptical) system surrounded by colder fluid (Bodvarsson, 1972). This model is used to estimate the time of the cold-front breakthrough. The size of the system, which is highly uncertain, has been estimated to be at least 0.5 km^3, on the basis of geophysical data. The principal results are presented in Fig. 6 below for a few production scenarios, and for two different volumes. Reservoir porosity between 5 and 15% is assumed.

This analysis shows that it should be possible to maintain constant production temperature in the Hamar field, at 40 kg/s average production, for more than 200 years, assuming the conservative reservoir volume. It may also be mentioned for comparison that it only takes about 15-45 years to replace the water in storage in the conservative reservoir volume at a production rate of 40 kg/s.

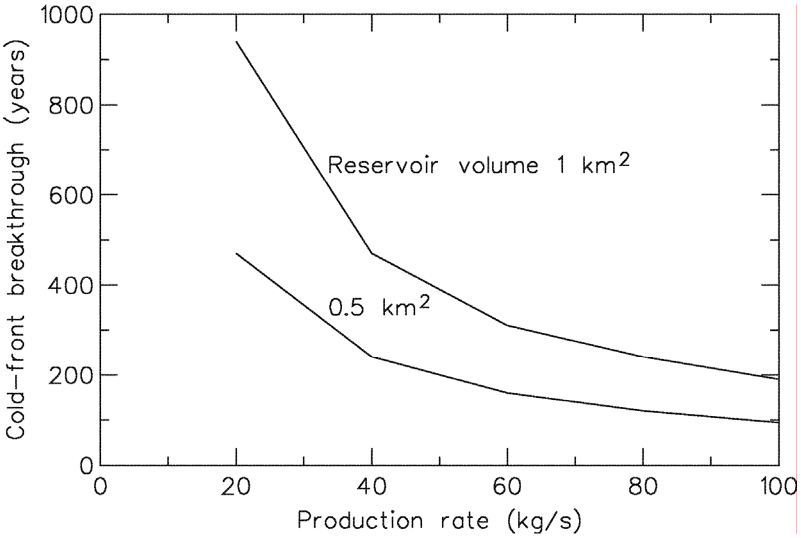

FIGURE 6: Estimated cold-front breakthrough times for the Hamar geothermal system.

The above results clearly indicate that the long-term production potential of the Hamar geothermal reservoir is limited by energy-content rather than pressure decline (lack of water). We can also conclude that the sustainable rate of production is > 40 kg/s and that $E_0 > 11$ MW_t (assuming a reference temperature of 0°C). It should be mentioned that new developments in field management, such as tapping fluid at greater depth, will increase the accessible reservoir volume and hence E_0.

4.2 The Nesjavellir High-Enthalpy Systems, SW-Iceland

Assessing the sustainable potential of the many high-enthalpy geothermal systems, utilized for electricity production throughout the world, is more complicated than for low-temperature case such as the Hamar case introduced above. This is because of the more complicated interaction between changes in pressure conditions and energy content (i.e. through phase changes) in high-enthalpy situations. Such work is under way, however, in Iceland, but only preliminary results are available as of yet. Here we'll present some results, and speculations, for the Nesjavellir geothermal system in SW-Iceland, which has been extensively studied and modelled in recent years.

The Nesjavellir geothermal system is part of the Hengill volcanic system located on the boundary between the North American and European crustal plates in SW-Iceland. It is characterized by a highly permeable system of NNE trending normal faults, continuous earthquake activity, frequent magma intrusions and intense surface activity. The geothermal potential of the region has been studied extensively since the late 1940's (Steingrímsson *et al.*, 2000; Björnsson *et al.*, 2003). More than twenty deep (1-2 km) wells have presently been drilled at Nesjavellir and the reservoir temperature is 250–340°C.

Utilization of the Nesjavellir geothermal system started in 1990 with the commissioning of a 100 MW_t thermal power plant, which supplied Reykjavík, the capital of Iceland, with hot water for space heating. In 1998 electricity production was initiated at Nesjavellir with the installation of two 30 MW_e turbines. At the same time thermal energy production was expanded to 200 MW_t. In the year 2001 the electrical capacity of the Nesjavellir power plant was expanded to 90 MW_e and the fourth 30 MW turbine came on line in September 2005. At the present mass extraction at Nesjavellir is of the order of 540 kg/s. Since 1985 reservoir pressure at Nesjavellir has dropped by about 7 bar.

Extensive modelling activity involving Nesjavellir, with the purpose of evaluating and assessing the geothermal system, has been ongoing since the middle of the 1980's (Steingrímsson *et al.*, 2000). A detailed three-dimensional numerical model developed in 1984-86 has been continuously revised and updated and during 2001-2003 a model covering all of the Hengill volcanic system was developed (Björnsson *et al.*, 2003). In addition, a simple lumped parameter model (see above) was recently developed to simulate pressure changes in the Nesjavellir reservoir (Axelsson, 2003).

The principal results of the lumped parameter modelling study are presented in Fig. 7 below. These are simulated pressure decline data (measured as water level) from a centrally located observation well (NJ-15) and pressure decline predictions by an open (optimistic) and a closed (pessimistic) lumped model, for a 120 MW_e future production scenario.

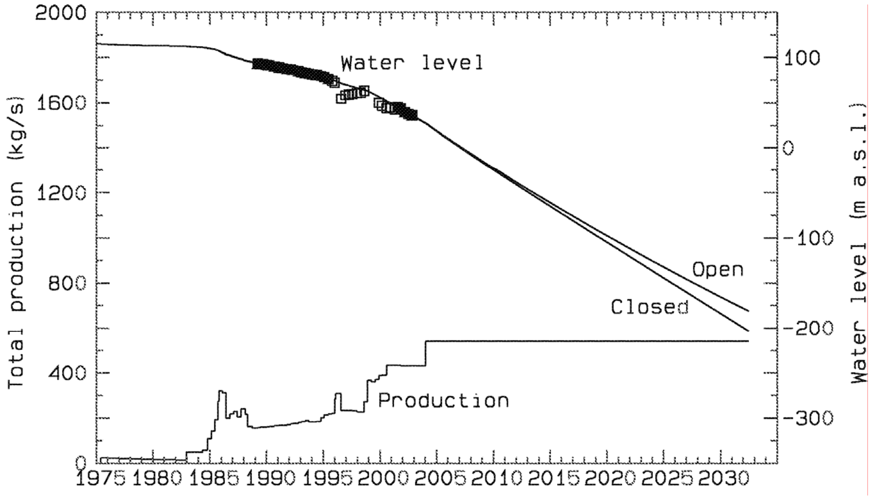

FIGURE 7: Pressure decline data (measured as water level) from an observation well (NJ-15) at Nesjavellir simulated by a lumped parameter model and pressure decline predictions, calculated by an open (optimistic) and a closed (pessimistic) model, for a 120 MW_e future production scenario. Also shown is the total mass extraction from the field.

The results in Fig. 7 show that the production needed for the 120 MW_e generation of electricity, about 540 kg/s, will cause a pressure draw-down of the order of 30 bar up the year 2035. This is not considered too drastic. The results indicate, however, that production at this rate can't be sustained for a period of 200 years because of continuously increasing pressure draw-down. In addition some reservoir cooling may be expected because of colder boundary recharge. An ultra simple estimation, similar to the one presented above for Hamar, indicates that significant cooling will start to take place within 60-100 years. In addition some boiling induced cooling may be expected. It may be mentioned here that the pressure decline predicted (Fig. 7) shows that properly planned reinjection should be beneficial for the operation of the Nesjavellir field. Such reinjection needs care, however, if emphasis is placed on maintaining the planned 120 MW_e electricity production.

This situation has been studied further by Björnsson and Hjartarson (2003). Firstly, they predict almost the same pressure draw-down as the lumped parameter model, which indicates that the pressure decline predictions presented are fairly reliable. Secondly, they use the Hengill-model to study how reservoir conditions (pressure and temperature as well as mass and energy) may recover after the 30-year period of large-scale production, if production is stopped. In other words, they study how reversible the effects of this production are.

Björnsson and Hjartarson (2003) calculate the recovery for a period of several hundred years. This is not commonly included in conventional reservoir modelling studies. The work of Pritchett (1998) comes to mind, however. The principal results are presented in Fig. 8, which shows changes in reservoir pressure and temperature at Nesjavellir during the 30-year period of intense production, as well as for the following 250 years of recovery. The figure shows that pressure, which should be accurately calibrated, recovers on a time-scale comparable to the time-scale of production. According to the model, temperature recovers on a much longer time scale. This is not unexpected considering the physics involved, yet it should be mentioned that the temperature changes are not well calibrated in the model because of limited data on temperature changes. An important point, however, is that the model only predicts a small temperature change at the end of the 30-year period, or 4-5°C, which is about 1,5% of the reservoir temperature.

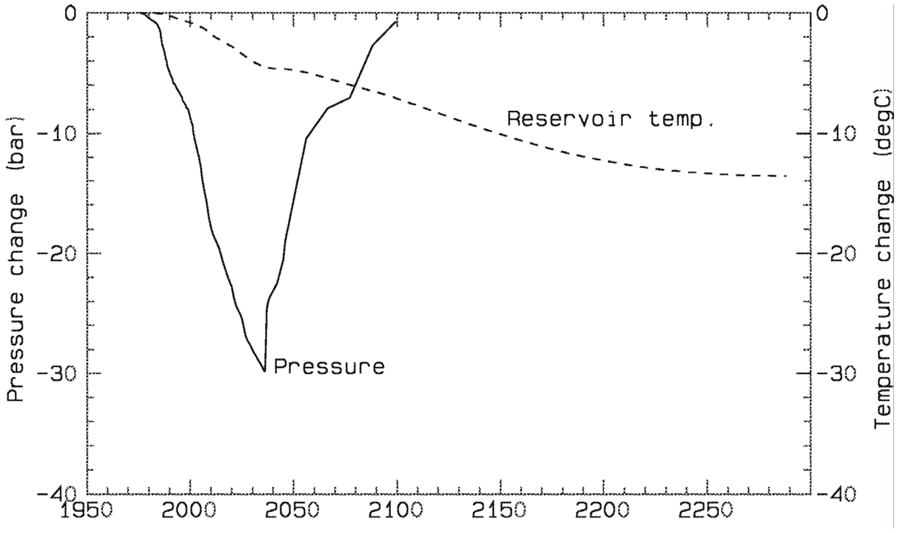

FIGURE 8: Calculated changes in reservoir pressure and temperature at Nesjavellir during the 30-year period of intense production (Fig. 7), and for the following 250 years of recovery (production stopped in 2036). Based on Björnsson and Hjartarson (2003).

The principal result of the work of Björnsson and Hjartarson (2003) is that the effects of intense, or even excessive, production at Nesjavellir until 2036 should be reversible. Also that after a recovery period of approximately the same length as the production period sustainable utilization at a reduced rate of production could follow. Such a production pattern is more along the lines proposed by Lovekin (2000).

The lumped parameter model for Nesjavellir (open version) has been used to extend the predictions presented in Fig. 7 for a 200 year production history, as in the case of Hamar.
This was done to estimate roughly the possible rate of production following the period of intense production ending in 2036. The results are presented in Fig. 9. If it is assumed that a pressure drop of the order of 30 bar or less is acceptable then it shows that the average production will have to be reduced to 180 kg/s or less, which corresponds to 1/3 of the production up to 2036.

Several issues concerning Fig. 9 should be noted. Firstly, that the limit of a 30 bar pressure maximum draw-down (300 m water level drop) may be too conservative. Secondly, that considerable changes in energy content may occur in the Nesjavellir system during this 200 year period such that it will become less suitable for electricity production. Energy production for direct uses will, however, most likely be feasible the whole period. Thirdly, that if the system is allowed to recover after 2036, as discussed above, production well above 180 kg/s (perhaps 400–500 kg/s) may be started again for a period of 30–50 years. This would constitute a kind of periodic production pattern. We must emphasize, however, that this work is still in progress and that sustainable management of the Nesjavellir system needs further study.

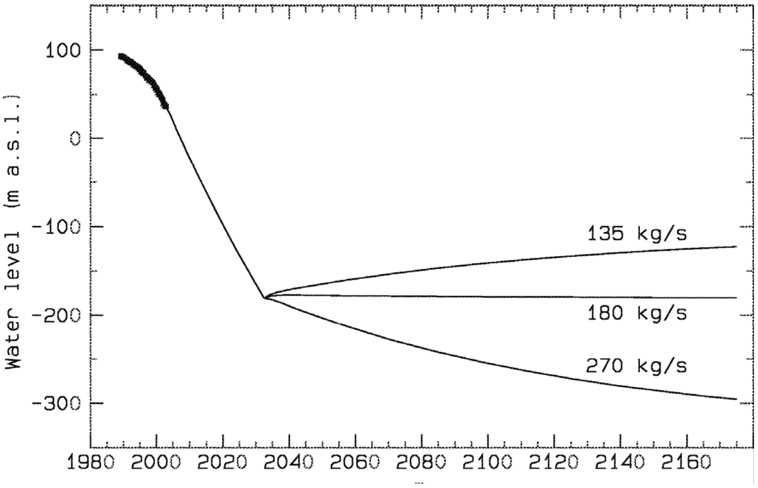

FIGURE 9: Predicted pressure changes (presented as water level changes) in the Nesjavellir systems during a 200-year production history with intense/excessive production (540 kg/s) up to 2036.

5. CONCLUDING REMARKS

To conclude, the following should be emphasized: Sustainable geothermal utilization involves energy production at a rate, which may be maintained for a very long time (100-300 years). This requires efficient management in order to avoid overexploitation, which mostly occurs because of lack of knowledge and poor understanding as well as in situations when many users utilize the same resource, without common management. Energy-efficient utilization, as well as careful monitoring and modelling, are essential ingredients in sustainable management. Reinjection is also essential for sustainable utilization of geothermal systems, which are virtually closed and with limited recharge.

Two case studies have been presented involving geothermal resources, of highly contrasting nature. It is proposed that both of them may be managed in a sustainable manner. The Hamar low-temperature geothermal system in N-Iceland is an example where modelling based on long-term monitoring has been employed to estimate the sustainable potential of a geothermal system. The results indicate that the long-term (200 years) production potential of the system is limited by energy-content rather than pressure decline (lack of water). The sustainable rate of production at Hamar is estimated to be greater than 40 kg/s, corresponding to more than 11 MW_t.

Production from the Nesjavellir high-temperature geothermal field, inside the volcanic zone in SW-Iceland, is planned at 120 MW_e, and 400 MW_t, for the next decades. Preliminary results indicate this production can't be maintained in a sustainable manner for 100-300 years. The effects of this intense production should be reversible, however, according to a modelling study. After a recovery period of approximately the same length as the production period, sustainable utilization at a reduced rate of production could follow. It must be emphasized that these are only preliminary results and that further work is required.

It must be emphasized that the estimates for sustainable potential presented here are believed to be considerably greater than the recharge to the systems in the natural state. This is, firstly, because they are based on a period of 100–300 years, which is a very short period compared with the geological time scale. It is, however, an appropriate timescale when considering human endeavours but very long when considering economic aspects in a market economy. Secondly, reinjection adds to the recharge where it is applied.

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