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Sustainable Management of Geothermal Resources and Utilization for 100 – 300 Years

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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. Three case studies are presented where reservoir modeling is used to analyze sustainable management of the corresponding resources. One of these involves a small low-temperature geothermal system in Iceland, where modeling based on long-term monitoring has been employed to estimate the sustainable potential of the system. Another involves the geothermal resources in a deep sedimentary basin in the P.R. of China. This second resource is of an entirely different nature, and requires full reinjection for sustainable utilization. The third case study involves a high-temperature geothermal system in Iceland, which is utilized for combined thermal energy and electricity production. Modeling 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

Geothermal energy is a renewable, environmentally friendly energy-source based on the internal heat of the Earth. It may be associated with volcanic activity, hot crust at depth in tectonically active areas or permeable sedimentary layers at great depth. Thermal springs have been used for bathing, washing and cooking for thousands of years, while geothermal electricity production, and large-scale direct use, started during the first half of the twentieth century. Geothermal energy is now utilized in more than 50 countries worldwide.

With a rapidly growing world-population, and ever-increasing environmental concerns, sustainable development has become an issue of crucial importance for mankind. Geothermal resources have the potential of contributing significantly to sustainable energy use in many parts of the world. The production capacity of geothermal systems is quite variable and different systems respond differently to production, depending on their geological setting and nature. Therefore, comprehensive management is essential for the sustainable use of all geothermal resources.

In the following sustainable utilization of geothermal resources will be discussed in view of examples of available long-term case histories and relevant definitions. Consequently, the principal ingredients of sustainable geothermal resource management will be discussed. The core of the paper is devoted to three case studies with particular emphasis on sustainable management of the corresponding resources. One of the studies involves the Hamar low-temperature geothermal system in N-Iceland, another one the geothermal resources existing in the deep sedimentary basin below the city of Beijing, in the P.R. of China, and the third one the Nesjavellir high-enthalpy (high-temperature) geothermal system, which is part of the Hengill volcanic complex in SW-Iceland.

2. SUSTAINABLE UTILIZATION

The term *sustainable development* became fashionable after the publication of the Brundtland report in 1987 (World Commission on Environment and Development, 1987). There, 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 inherently rather vague and it has often been understood somewhat differently.

At the core of the issue of sustainable development is the utilization of the various natural resources available to us today, including the worlds' energy resources. *Sustainability* of geothermal energy production is a topic that has received limited attention, however, even though the longevity of geothermal production has long been the concern of geothermal operators (Wright, 1999; Stefansson, 2000; Rybach *et al.*, 2000; Cataldi, 2001). The terms *renewable* and *sustainable* are, in addition, often confused. The former concerns the nature of a resource while the latter applies to how a resource is utilized (Stefansson and Axelsson, 2005).

The energy production potential of geothermal systems is highly variable. It is primarily determined by pressure decline due to production, but also by the available energy content. Pressure declines continuously with time, particularly in systems that are closed or with small recharge. Production potential is, therefore, often limited by lack of water rather than lack of thermal energy. The nature of the geothermal systems is such that the effect of "small" production is so limited that it can be maintained for a very long time (hundreds of years). The effect of "large" production is so great, however, that it can't be maintained for long.

In many cases several decades of experience have shown that by maintaining production below a certain limit a geothermal system reaches a certain balance, which may be maintained for a long time. Fig. 1 shows such an examples from the Laugarnes geothermal system 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. Another example is the Matsukawa geothermal system in Japan, where relatively constant electrical energy production (23.5 MW_e) has been maintained for close to four decades (Hanano, 2003). Fig. 2 shows the average yearly steam production at Matsukawa.

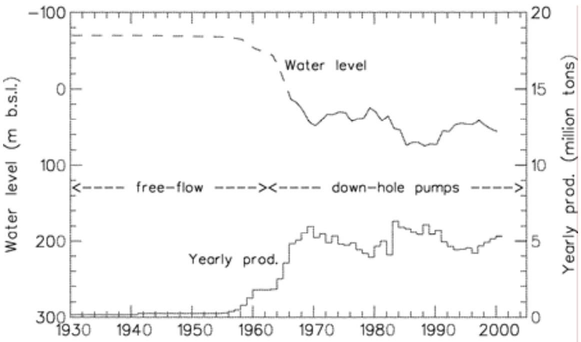

Figure 1: Production and water-level history of the Laugarnes geothermal system in SW-Iceland.

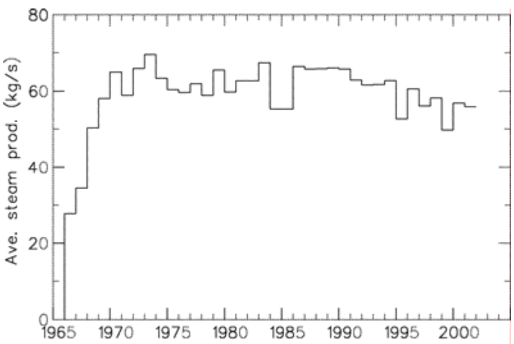

Figure 2: The production history of the Matsukawa geothermal system in Japan. Based on data presented by Hanano (2003).

Other examples are available where production has been so great that equilibrium was not attained. A good example of this is the Geysers geothermal field in California. Twenty geothermal power plants, with a combined capacity of more than 2000 MW, 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 cases such as Laugarnes and Matsukawa 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.

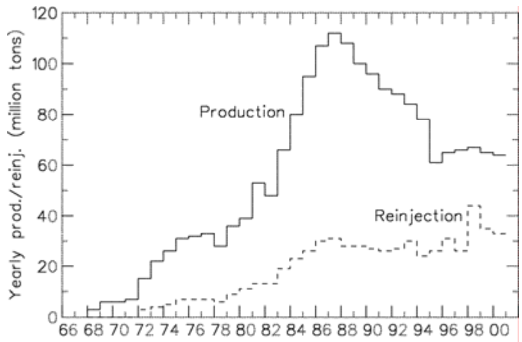

Figure 3: Production- and reinjection history of The Geysers geothermal field in California (Barker, 2000).

Axelsson *et al.* (2001) propose the following definition for the term "*sustainable production of geothermal energy from an individual geothermal system*". This definition does neither consider economical aspects, environmental issues, nor technological advances, all of which may be expected to fluctuate with the times.

For each geothermal system, and for each mode of production, there exists a certain level of maximum energy production, $\boldsymbol{E_0}$, 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.***

This definition applies to the total extractable energy, and depends in principle on the nature of the system in question, but not on load-factors or utilization efficiency. It also depends on the mode of production, which may involve spontaneous discharge, pumping, injection or periodic production. It may, furthermore, be expected to increase with technological advances. The value of $\mathbf{E_0}$ is not known a priori, but it may be estimated, through modeling, on the basis of exploration and production data as they become available. It must be emphasized that this definition is simply based on the Brundtland definition, but does not imply economical sustainability, which normally is considered on a much shorter time scale, normally of the order of 30 years.

If energy production from a geothermal system is within the sustainable limit defined above one may assume that the stored energy is depleted relatively slowly and that the energy in the reservoir is renewed at approximately the same rate as it is extracted at. Once again the Laugarnes system provides a good example. To maintain such a semi-steady state for a long time thus requires the renewable part of the underlying resource to be relatively powerful. Yet it is likely that the "volume of influence" of the geothermal energy extraction is very large and that the renewability is to some degree supported by energy extraction from the outer and deeper parts of the geothermal system in question.

3. GEOTHERMAL MANAGEMENT

Geothermal resource management involves controlling energy extraction from geothermal systems underground so as to maximize the resulting benefits, without over-exploiting the resource. It involves deciding between different courses of action aimed at improving operating conditions, addressing unfavorable reservoir conditions, which may have evolved, or incorporating improvements in production strategy (Stefansson *et al.*, 1995, Axelsson and Gunnlaugsson, 2000). The operators of a geothermal resource must have some idea of the possible results of different courses of action, to be able to make these decisions.

The generating capacity of geothermal systems is often poorly known and they often respond unexpectedly to long-term energy extraction. This is because the internal structure, nature and properties of these complex underground systems are often poorly known and can only be observed indirectly. Successful management relies on proper understanding of the geothermal system involved, which in turn relies on adequate information on the system. The pressure decline, which is the primary factor in determining generating capacity, is for example controlled by the size of a system, permeability of the rock and water recharge (i.e. boundary conditions).

When geothermal systems are over-exploited, production from the systems has to be reduced, often drastically. Overexploitation mostly occurs for two reasons. Firstly, because of inadequate monitoring and data collection, understanding of systems is poor and reliable modeling is also not possible. Therefore, the systems respond unexpectedly to long-term production. Secondly, when many users utilize the same resource/system without common management or control. Examples of the latter are The Geysers, mentioned above, and large sedimentary basins in Europe and the P.R. of China.

In addition to energy-efficient utilization, monitoring, modeling and reinjection may be looked upon as the main ingredients in efficient, modern geothermal resource management (Axelsson and Gunnlaugsson, 2000; Axelsson *et al.*, 2002). Careful monitoring, throughout the exploration- and exploitation history of a geothermal reservoir, leads to proper understanding of its nature and successful management of the resource.

Mathematical models are developed on the basis of these data, with the purpose of extracting information on conditions, nature and properties of a system, calculate response predictions and estimate production potential, and for management purposes by estimating the outcome of different management actions.

Finally, reinjection should be considered an integral part of any modern, sustainable, environmentally friendly geothermal utilization. It started out as a method of waste-water disposal for environmental reasons, but is now also being used to counteract pressure draw-down, i.e. as man-made water recharge, and to extract more thermal energy from reservoir rock (Stefansson, 1997). One of the main problems/ concerns associated with injection is the possible cooling of production wells (thermal breakthrough), which has discouraged the use of injection in some cases.

4. CASE STUDIES

The remainder of this paper is devoted to three case studies related to sustainable management. One of these is the Hamar low-temperature geothermal system in Central N-Iceland, where modeling based on long-term monitoring has been employed to estimate the sustainable potential of the system. The second study involves the geothermal resources, which are known to exist in the deep sedimentary basin below the city of Beijing, in the P.R. of China. These resources are of an entirely different nature, and require full reinjection for sustainable utilization, as well as common management, to avoid overexploitation. The third 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 modeling. A simple method of modeling 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.

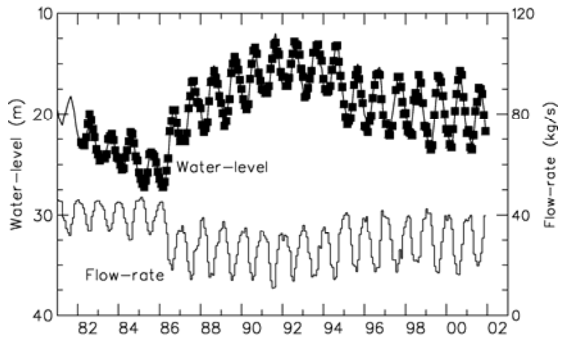

Figure 4: Last two decades of the production history of the Hamar geothermal system, the water-level history having been simulated by a lumped-parameter model (squares = measured data, line = simulated data).

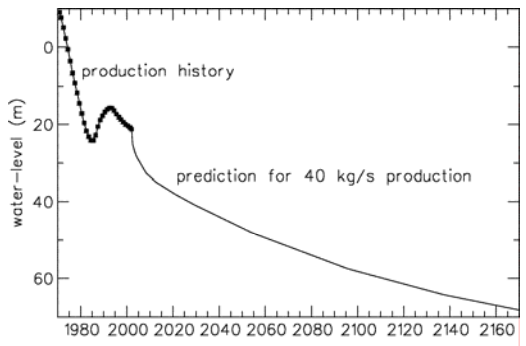

Figure 5: Predicted water-level (pressure) changes in the Hamar geothermal system for a 200-year production history.

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.

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.

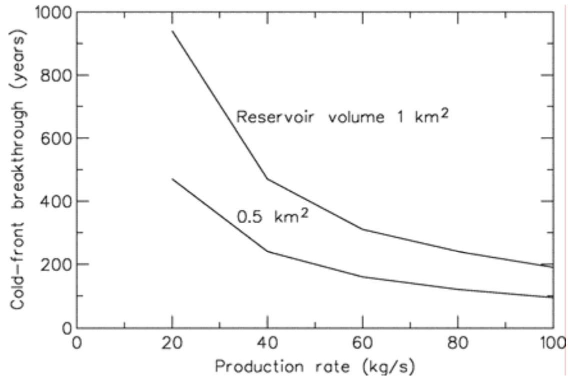

Figure 6: Estimated cold-front breakthrough times for the Hamar geothermal system.

4.2 Geothermal Resources under Beijing, P.R. of China

Beijing City is situated on top of a large and deep sedimentary basin where geothermal resources have been found at depth. These resources owe their existence to sufficient permeability and porosity at great depth (1-4 km) where the rocks are hot enough to heat water to exploitable temperatures. Major faults and fractures also play a role in sustaining the geothermal activity through providing the main flow paths for circulating water as well as acting as aquicludes. The water recharge to the basin is believed to be precipitation falling in the hills and mountains on the outskirts of the basin, which percolates to great depth and, consequently, rises as hot water through some of the permeable faults/fractures.

Beijing basin has been divided into ten geothermal areas on the basis of geological and geothermal conditions. The best known are the Urban and Xiaotangshan areas, which have been utilized since the 1970's and 1980's, respectively (Liu *et al.*, 2002). Somewhat over 200 geothermal wells have drilled in Beijing since that time, ranging in depth from 800 to 3600 m. Plans are being made to increase geothermal utilization in Beijing, in particular for space heating, in order to help battle the serious air pollution facing the city. The reservoir rocks in the Urban and Xiaotangshan systems are mostly limestone and dolomite and reservoir temperature ranges from about 40 to 90 °C. The yearly production from the Urban and Xiaotangshan fields in recent years has corresponded to an average production of about 110 and 120 kg/s, respectively. This has resulted in a water level draw-down of the order of 1.5 m/year in the two fields. The water level has declined at an apparently constant rate in spite of the average production remaining relatively constant. This clearly indicates that the underlying reservoirs have limited recharge and, in fact, act as nearly closed hydrological systems (Axelsson *et al.*, 2002).

One of the Beijing geothermal fields is the so-called Shahe field. It is located in the north part of the city, south of the Xiaotangshan field, and has been evaluated by Axelsson (2001), Xu, (2002), Axelsson *et al.* (2002) and Hjartarson *et al.* (2005). A few wells have been drilled in the Shahe field, most of them poorly productive, while recently a few more productive wells have been drilled. Data collected through these wells, including some production monitoring data, have been simulated by lumped parameter models

(Xu, 2002; Axelsson *et al.*, 2002) and a detailed numerical model (Hjartarson *et al.* 2005). The results show clearly that the Shahe reservoir is an almost closed system (with limited recharge). Water level predictions show that a considerable, constantly increasing, water-level draw-down may be expected in the reservoir. Predictions with reinjection show that reinjection will be essential for sustainable utilization of this reservoir. Without reinjection its' potential appears to be quite limited. The Shahe reservoir suffers, in fact, from a lack of water recharge.

Liu *et al.* (2002) present a study of one of the two main Beijing geothermal fields discussed above, the Urban field. This study included lumped parameter modeling that now has been expanded to evaluate the fields' sustainable production potential in a manner similar that applied to the Hamar system, presented above. The Urban field has been utilized since 1971 and excellent pressure (water-level) and production monitoring data are available since the late 1970's. Fig. 7 shows these data as well as water level data simulated by an updated version of the lumped parameter model of Liu *et al.* (2002). It shows clearly the constantly declining pressure, in spite of stable, or even declining, yearly production.

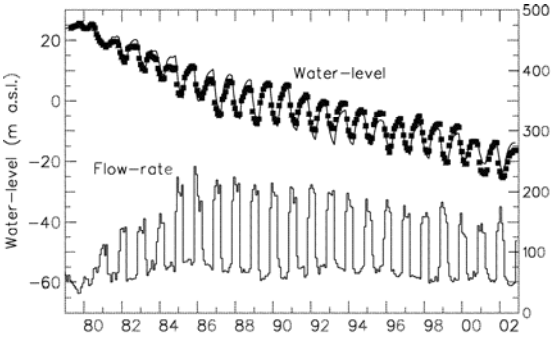

Figure 7: The production history of the Urban geothermal field in Beijing with the water-level history simulated by a lumped-parameter model (squares = measured data, line = simulated data)

The lumped parameter model for the Urban field was, consequently, used to predict pressure (water level) changes in the underlying geothermal system for a 200-year production history, as in the case of the Hamar field, in order to attempt to evaluate the sustainable production capacity of the field. Fig. 8 shows two examples of the results. On one hand, prediction for a 100 kg/s long-term average production, without any reinjection, which is close to the present average yearly production. This prediction indicates that pressure will decline continuously, having dropped about 20 bar at the end of the prediction period. Such a great decline is probably not acceptable at the present time. Whether it will be acceptable in the 21st century is impossible to ascertain. The sustainable potential of the Urban field is, therefore, less than 100 kg/s on the average if reinjection is not applied.

On the other hand, Fig. 8 presents a prediction for a 200 kg/s long-term average prediction with approximately 80% reinjection. In this case the pressure drop is slightly more than half of what it was in the previous case and a pressure drop of the order of 10 bar will most likely be acceptable. Therefore, it may be stated that the sustainable average rate of production from the Urban field is likely to be greater than 200 kg/s, or double the present rate, if "full" (80-90%) reinjection is applied. This corresponds to an $E_0 > 63$ MW_t (assuming an average production temperature of 75°C and a reference temperature of 0°C).

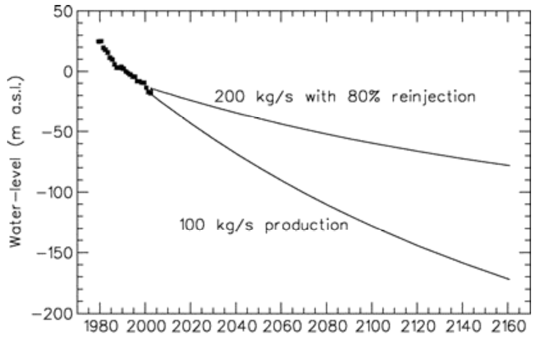

Figure 8: Predicted water-level (pressure) changes in the Urban geothermal field in Beijing for a 200-year production history

More than sufficient thermal energy should be in-place in the Beijing geothermal reservoirs to support long-term reinjection, however, because of the great volume of resource, and reinjection will provide a kind of man-made recharge. Preliminary calculations support this, yet it is likely that some production wells will experience cooling during the long time-span considered. This may be met through resource management that gives available wells a variable role and involves drilling of new wells as required.

These results for the Xiaotangshan and Shahe fields reviewed here, as well as the new modeling results for the Urban field, clearly indicate that reinjection will be essential if plans for increased use of the geothermal resources in Beijing are to materialize in a sustainable manner. Reinjection has not been part of the management of the Beijing resources so far; therefore, careful testing is essential for planning of future reinjection. Such testing has been limited in Beijing up to now, and not enough information is thus available to estimate the sustainable potential (E_0) of all the Beijing resources.

Another important aspect is essential for sustainable management of the geothermal resources in Beijing, and to avoid over-exploitation and over-investment in deep wells and surface equipment. This is efficient general management of the geothermal resources, because many different users may be utilizing the same reservoir. The production possible from a specific well will most certainly be limited (reduced) by interference from other nearby production wells. Because the resources are limited, utilization of different wells, in different areas, needs to be carefully harmonized.

4.3 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 cases such as the two cases 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 modeled 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 2000 the electrical capacity of the Nesjavellir power plant was expanded to 90 MW_e and plans are underway to expand it soon by an additional 30 MW_e. At the present mass extraction at Nesjavellir is of the order of 440 kg/s. Since 1985 reservoir pressure at Nesjavellir has dropped by about 7 bar.

Extensive modeling 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 modeling study are presented in Fig. 9 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.

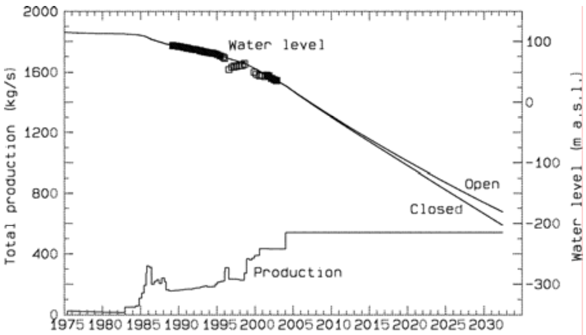

Figure 9: Pressure decline data (measured as water level) from an observation well (NJ-15) at Nesjavellir simulated by a lumped parameter model and pressure decline predictions, calculated by an open (optimistic) and a closed (pessimistic) model, for a 120 MW_e future production scenario. Also shown is the total mass extraction from the field.

The results in Fig. 9 show that the production needed for the proposed 120 MW_e electrical generation, 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. 9) 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 modeling studies. The work of Pritchett (1998) comes to mind, however. The principal results are presented in Fig. 10, 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.

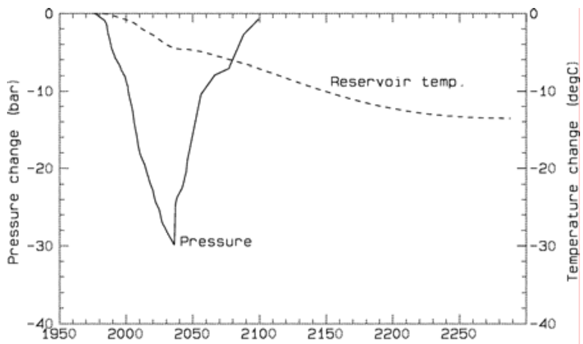

Figure 10: Calculated changes in reservoir pressure and temperature at Nesjavellir during the 30-year period of intense production (Fig. 9), and for the following 250 years of recovery (production stopped in 2036). Based on Björnsson and Hjartarson (2003).

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. 9 for a 200 year production history, as in the cases of Hamar and the Urban field. 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. 11. 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.

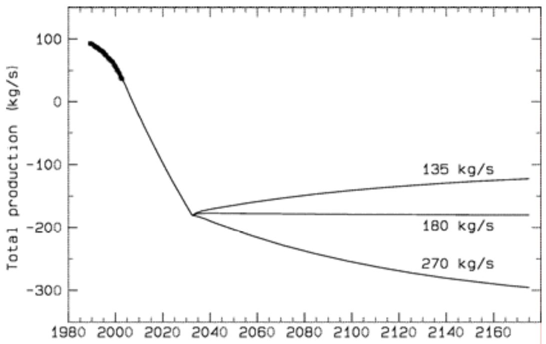

Figure 11: Predicted pressure changes (presented as water level changes) in the Nesjavellir systems during a 200-year production history with intense/excessive production (540 kg/s) up to 2036.

Several issues concerning Fig. 11 should be noted. Firstly, that the limit of a 30 bar pressure maximum draw-down 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.

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 modeling, are essential ingredients in sustainable management. Reinjection is also essential for sustainable utilization of geothermal systems, which are virtually closed and with limited recharge.

Three case studies have been presented involving geothermal resources, of highly contrasting nature. It is proposed that all of them may be managed in a sustainable manner. The Hamar low-temperature geothermal system in N-Iceland is an example where modeling 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.

The geothermal resources in the sedimentary basin below the city of Beijing, P.R. of China, appear to be vast. Yet, available information shows that they are limited by lack of fluid recharge rather than lack of thermal energy. Therefore, reinjection, is a prerequisite for their sustainable utilization. Common management, to harmonize the production by different users, and minimize interference, is also essential, as well as energy-efficient utilization. Modeling results for the Urban field in Beijing indicate that its' sustainable potential may be of the order of 200 kg/s, on the average, with 80% reinjection.

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 modeling 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 endeavors 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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