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SUSTAINABLE UTILIZATION OF GEOTHERMAL RESOURCES FOR 100 – 300 YEARS

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ABSTRACT

Geothermal resources have the potential of contributing significantly to sustainable development in many parts of the world. Sustainable management of a geothermal resource involves utilization at a rate, which may be maintained for a very long time (100-300 years). The energy production potential of geothermal systems is primarily determined by the pressure decline caused by production. Overexploitation of geothermal systems mostly occurs because of poor understanding, due to inadequate monitoring, and when many users utilize the same resource without common management. Careful monitoring and modeling, as well as energy-efficient utilization, are essential ingredients in sustainable management. Reinjection is also essential for sustainable utilization of geothermal systems, which are virtually closed and with limited recharge. The Hamar low-temperature geothermal system in the volcanic lava-pile of Central N-Iceland and the low-temperature geothermal resources in the sedimentary basin below the city of Beijing, P.R. of China have been utilized for decades. They are examples of geothermal resources, of highly contrasting nature, which may each be managed in a sustainable manner. The sustainable potential of the Hamar system is estimated, through modeling, to be greater than 40 kg/s of 65°C water. Reinjection is essential for sustainable management of the Beijing resource. The Nesjavellir high-temperature geothermal field is located inside the volcanic zone in SW-Iceland. Production from the field is planned at 120 MW_e, and 300 MW_t, for the next decades. This production can't be maintained in a sustainable manner for 100-300 years, but the impact appears to be reversible and the field may likely be utilized at a reduced rate, in a sustainable manner following a 30-year period of excessive utilization.

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 this paper sustainable utilization of geothermal resources will be discussed in view of some available long-term case histories and relevant definitions. Consequently, the principal ingredients of sustainable geothermal resource management will be discussed. The paper is concluded by a discussion of 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.

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.

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. Figure 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. 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 good example is the Matsukawa geothermal system in Japan, where relatively constant electrical energy production (23.5 MW_e) has been maintained for more than three decades (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 Figure 2. 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.

Axelsson *et al.* (2001) propose the following definition for the term "*sustainable production of geo-thermal 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, 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 E_0 it cannot be maintained for this length of time. Geothermal energy production below, or equal to E_0, is termed ***sustainable production*** *while production greater than E_0 is termed* ***excessive production.***

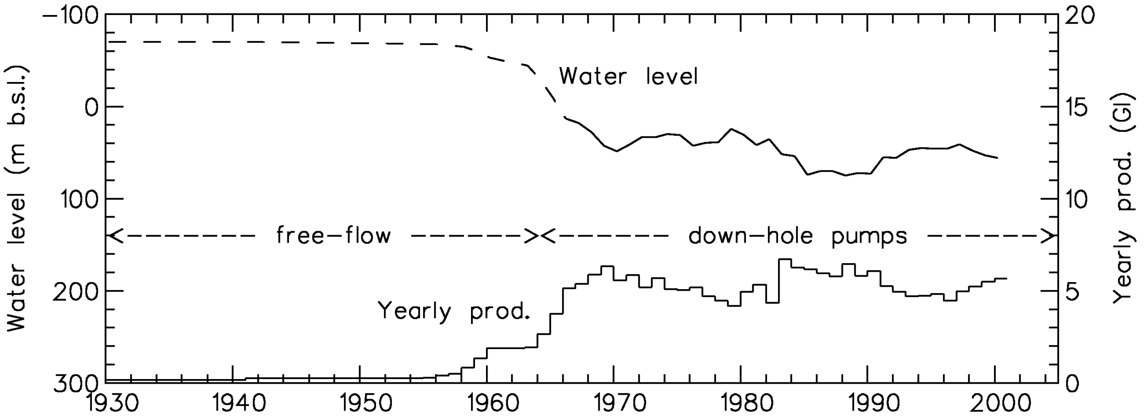

Figure 1. The production and water-level history of the Laugarnes geothermal system in SW-Iceland.

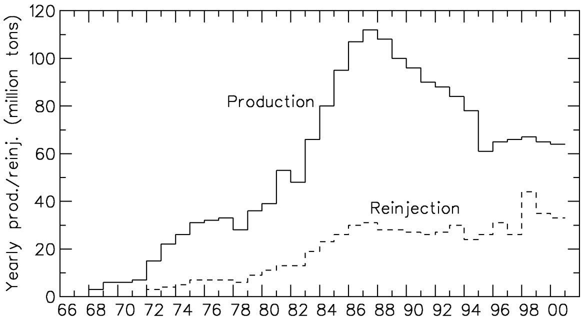

Figure 2. Production- and reinjection history of The Geysers geothermal field in California (Barker, 2000).

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 on the basis of exploration and production data as they become available. Figure 3 presents a schematic drawing illustrating the difference between sustainable and excessive production.

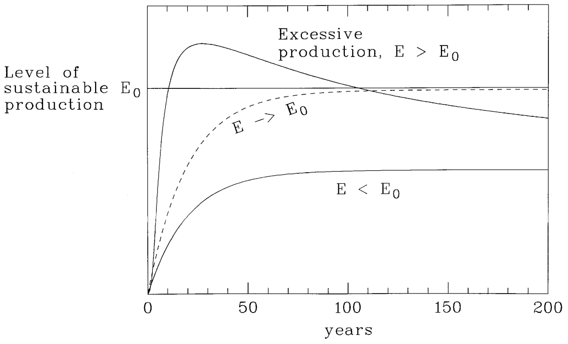

Figure 3. A schematic figure illustrating the difference between sustainable and excessive production.

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.

CASE STUDIES

We conclude this paper by discussing 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. This resource is of an entirely different nature, and requires 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.

The Hamar Geothermal System, 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 Figure 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 utilised in a sustainable manner during the last three decades. The production history is too short, however, to establish whether the current level of utilisation 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.

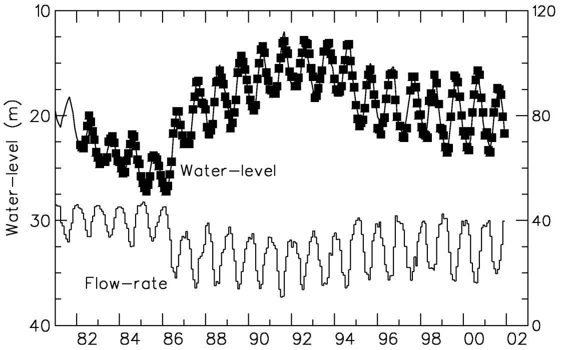

Figure 4. Last two decades of the production history of the Hamar geothermal system, the water-level history having been simulated by a lumped-parameter model (squares = measured data, line = simulated data).

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 Figure 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.

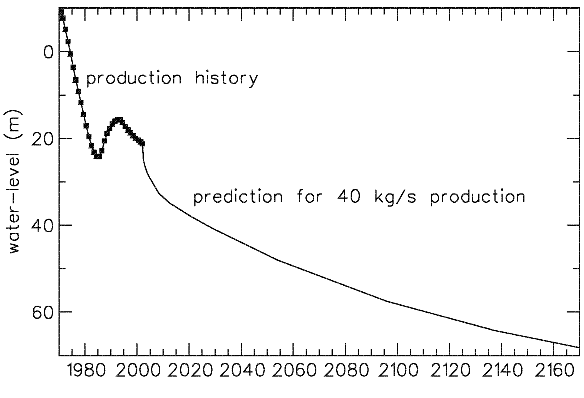

Figure 5. Predicted water-level (pressure) changes in the Hamar geothermal system for a 200-year production history.

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 below, for a few production scenarios, and for two different volumes. Reservoir porosity between 5 and 15% is assumed.

Table 1. Estimated cold-front breakthrough times for the Hamar geothermal system.

Production (kg/s)	Volume = 0.5 km^3	Volume = 1.0 km^3
20	470 years	940 years
40	240 years	470 years
60	160 years	310 years
80	120 years	240 years
100	94 years	190 years

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.

Geothermal Resources under Beijing, P.R. 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. The following is based on a discussion of the sustainable management of the Beijing geothermal resources by Axelsson *et al.* (2002). The reader is referred to that paper for more details.

The 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 70's and 80's, respectively (Liu *et al.*, 2002). 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 the yearly production from the Urban and Xiaotangshan fields corresponds 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 (see Figure 6). This clearly indicates that the underlying reservoirs have limited recharge and, in fact, act as nearly closed hydrological systems.

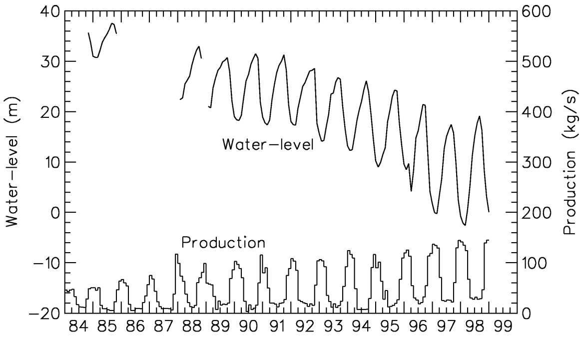

Figure 6. Part of the production and water-level history of the Xiaotangshan geothermal field in Beijing (Axelsson et al.*, 2002).*

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 an area of about 100km^2 (Axelsson, 2001; Xu, 2002). A few wells have been drilled in the Shahe field, most of them poorly productive. A well drilled in 1999-2000 in the Lishuiqiao area in the easternmost part of the field, ShaRe-6, turned out to be quite productive, however. It is drilled to a depth of 2418m, and produces from a Cambrian limestone formation. This well has been utilized for three years now with a careful monitoring program in place, and the data collected have been simulated by a lumped parameter model (Axelsson *et al.*, 2002). The results show clearly that the Shahe reservoir is an almost closed system (with limited recharge). Figure 7 shows water level predictions for well ShaRe-6 calculated by the lumped parameter model for an 8-year period, based on an average yearly production of 20 l/s. It is clear from the predictions 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. More than sufficient thermal energy is in-place in the geothermal reservoir, however, because of the great volume of resource, and reinjection will provide a kind of man-made recharge.

These results 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 the Beijing resources.

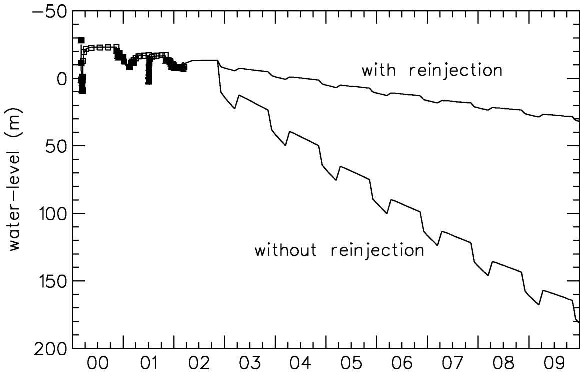

Figure 7. Results of modelling calculations for well ShaRe-6 in Beijing. Predictions for utilisation scenarios with 80-90% reinjection and without reinjection are shown.

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.

The Nesjavellir high enthalpy system, 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 Nesja-vellir 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 Figure 8 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.

The results in Figure 8 show that the production needed for the proposed 120 MW_e electrical generation, about 550 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 (Figure 8) 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.

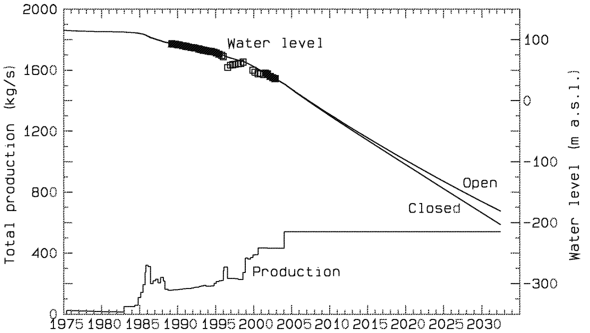

Figure 8. Pressure decline data (measured as water level) from an observation well (NJ-15) at Nesjavellir simulated by a lumped parameter model and pressure decline predictions, calculated by an open (optimistic) and a closed (pessimistic) model, for a 120 MW_e future production scenario. Also shown is the total mass extraction from the field.

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 Figure 9, 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.

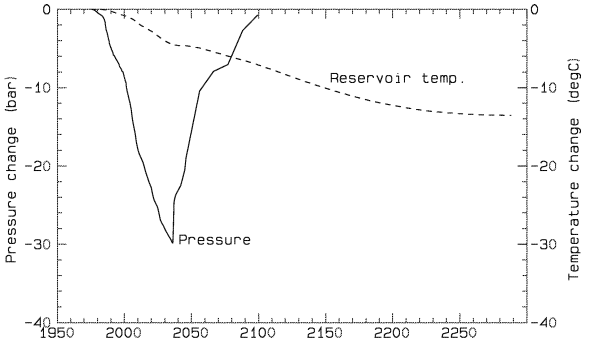

Figure 9. Changes in reservoir pressure and temperature at Nesjavellir during the 30-year period of intense production (Figure 8), and for the following 250 years of recovery (production stopped in 2036). Based on Björnsson and Hjartarson (2003).

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). We must emphasize that this work is still in progress and that sustainable management of the Nesjavellir system needs further study.

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 pre-requisite 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.

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.

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REFERENCES

Axelsson, G., 2003: A simple lumped parameter model of the Nesjavellir geothermal system – Pressure response predictions. Orkustofnun, report GAx-2003/04 (in Icelandic), Reykjavík, 6pp.

Axelsson, G., 2001: Preliminary assessment of the Shahe geothermal reservoir in Lishuiqiao, Beijing, P.R. of China. Orkustofnun, report GAx-2001/03, Reykjavík, 6pp.

Axelsson, G. and E. Gunnlaugsson (convenors), 2000: *Long-term Monitoring of High- and Low-enthalpy Fields under Exploitation*. International Geothermal Association, World Geothermal Congress 2000 Short Course, Kokonoe, Kyushu District, Japan, May 2000, 226pp.

Axelsson, G., V. Stefánsson and Y. Xu, 2002: Sustainable management of geothermal resources. *Proceedings of the International Symposium on Geothermal and the 2008 Olympics in Beijing*, Beijing, October 2002, 277-283.

Axelsson, G., A. Gudmundsson, B. Steingrimsson, G. Palmason, H. Armannsson, H. Tulinius, O.G. Flovenz, S. Bjornsson and V. Stefansson, 2001: Sustainable production of geothermal energy: suggested definition. *IGA-News*, Quarterly No. 43, January-March 2001, 1-2.

Barker, B., 2000: The Geysers: Past and Future. *Geothermal Resources Council Bulletin*, **29**, 163-171.

Björnsson, G. and A. Hjartarson, 2003: Reservoir model for the Hengill geothermal systems and future predictions for 120 MW electrical production at Nesjavellir and Hellisheidi. Iceland GeoSurvey (ÍSOR), report ÍSOR-2003/009 (in Icelandic), Reykjavík, 150pp.

Björnsson, G., A. Hjartarson, G.S. Bodvarsson and B. Steingrímsson, 2003: Development of a 3-D geothermal reservoir model for the greater Hengill Volcano in SW-Iceland. *Proceedings of the TOUGH Symposium 2003*, Berkeley, California, May 2003, 12pp.

Bodvarsson, G., 1972: Thermal problems in the siting of reinjection wells. *Geothermics*, **1**, 63-66.

Cataldi, R., 2001: Sustainability and renewability of geothermal energy. *Proceedings of the International Scientific Conference on Geothermal Energy in Underground Mines*, Ustron, Poland, November 2001, 4pp.

Hanano, M., 2003: Sustainable steam production in the Matsukawa geothermal field, Japan. *Geothermics*, **32**, 311-324.

Liu, J., X. Pan, Y. Yang, Z. Liu, X. Wang, L. Zhang and W. Xu, 2002: Potential assessment of the Urban geothermal field, Beijing, China. *Proceedings of the International Symposium on Geothermal and the 2008 Olympics in Beijing*, Beijing, October 2002, 211-217.

Lovekin, J., 2000: The economics of sustainable geothermal development. *Proceedings of the World Geothermal Congress 2000*, Kyushu-Tohoku, Japan, May-June 2000, 834-848.

Pritchett, J.W., 1998: Modeling post-abandonment electrical capacity recovery for a two-phase geothermal reservoir. *Geothermal Resources Council Transactions,* **22**, 521-528.

Rybach, L., T. Megel and W.J. Eugster, 2000: At what scale are geothermal resources renewable? *Proceedings of the World Geothermal Congress 2000*, Kyushu-Tohoku, Japan, May-June 2000, 867-872.

Steingrímsson, B., G.S. Bodvarsson, E. Gunnlaugsson, G. Gíslason and Ó. Sigurdsson, 2000: Modeling studies of the Nesjavellir geothermal field, Iceland. *Proceedings of the World Geothermal Congress 2000*, Kyushu-Tohoku, Japan, May-June 2000, 2899-2904.

Stefansson, V., 1997: Geothermal reinjection experience. *Geothermics*, **26**, 99-130.

Stefansson, V., 2000: The renewability of geothermal energy. *Proceedings of the World Geothermal Congress 2000*, Kyushu-Tohoku, Japan, May-June 2000, 883-888.

Stefansson, V., G. Axelsson, O. Sigurdsson and S.P. Kjaran, 1995: Geothermal reservoir management in Iceland. *Proceedings of the World Geothermal Congress 1995*, Florence, Italy, May 1995, 1763-1768.

World Commission on Environment and Development, 1987: *Our Common Future*. Oxford University Press, Oxford, 400pp.

Wright, P.M., 1999: The sustainability of production from geothermal resources. Lectures presented at the United Nations University Geothermal Training Programme, Reykjavik, September 1999, 42pp.

Xu, Y., 2002: Assessment and modelling of geothermal resources in the Lishuiqiao area, Beijing, P.R. of China. *UNU Geothermal Training Programme, Reports 2002*, report 17, Reykjavik, 335-358.