

# Sustainable management of geothermal resources

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## Abstract

Geothermal energy is a renewable, environmentally friendly energy-source most often associated with volcanic activity, hot crust at depth in tectonically active areas or deep and permeable sedimentary layers. The energy production potential of geothermal systems is primarily determined by the pressure decline caused by production. Sustainable management of a geothermal resource involves utilisation at a rate, which may be maintained for a very long time (100-300 years). Overexploitation of geothermal systems mostly occurs because of poor understanding, due to inadequate monitoring, and when many users utilise the same resource without common management. Careful monitoring and modelling, as well as energy-efficient utilisation, are essential ingredients in sustainable management. Reinjection is also essential for sustainable utilisation 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 geothermal resources in the sedimentary basin below the city of Beijing, P.R. of China have been utilised 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 modelling, to be greater than 40 kg/s of 65°C water.

*Keywords: Sustainable, management, monitoring, modelling, reinjection, Hamar, Beijing.*

## 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 utilised 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 utilisation 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 two case studies with particular emphasis on sustainable management of the corresponding resources. One of these involves the Hamar low-temperature geothermal system in

Iceland, and the other one geothermal resources existing in the deep sedimentary basin below the city of Beijing, in the P.R. of China.

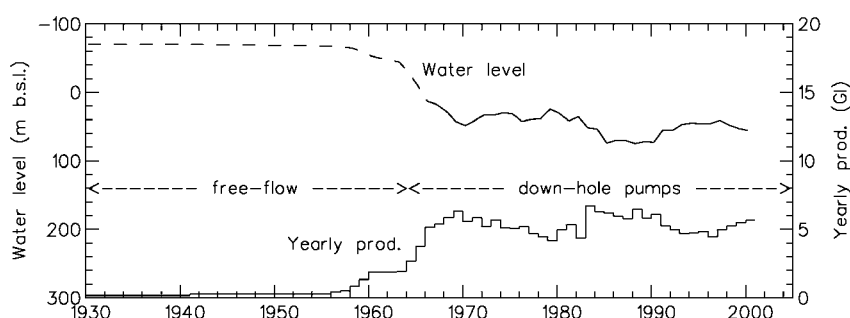
## 2 Sustainable utilisation

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 cannot 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. It shows that even though production was increased by an order of magnitude in the sixties, through the introduction of down-hole pumps, which resulted in a reservoir pressure drop corresponding to about 120 m of water level, production and water level have remained relatively stable during the last three decades. This indicates that



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

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) has been maintained for more than three decades (Hanano, 2002).

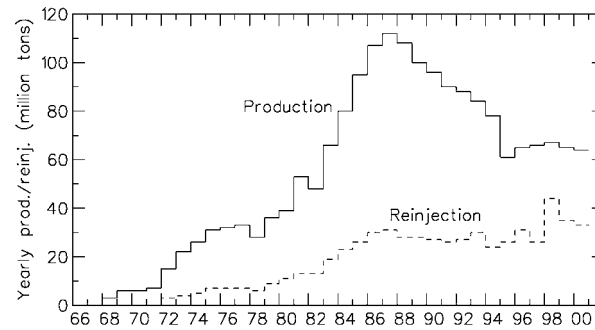
Other examples are available where production has been so great that equilibrium was not attained. A good example of this is the Geysers geothermal field in California. Twenty geothermal power plants, with a combined capacity of about 2000

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. 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.

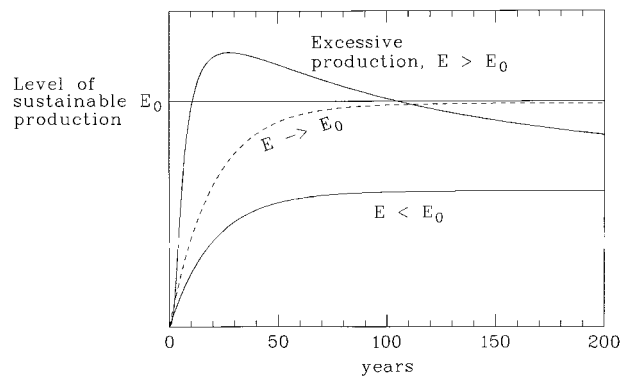
Axelsson *et al.* (2001) propose the following definition for the term “sustainable production of geothermal energy from an individual geothermal system”. This definition does neither consider economical aspects, environmental issues, nor technological advances, all of which may be expected to fluctuate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

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

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. The value of  $E_0$  is not known a priori, but it may be estimated on the basis of available data (by modelling). Fig. 3 presents a schematic drawing illustrating the difference between sustainable and excessive production.



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



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

### 3 Geothermal management

Geothermal resource management involves controlling energy extraction from geothermal systems underground so as to maximise the resulting benefits, without over-exploiting the resource. It involves deciding between different courses of action aimed at improving operating conditions, addressing unfavourable 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 modelling is also not possible. Therefore, the systems respond unexpectedly to long-term production. Secondly, when many users make use of 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 utilisation, monitoring, modelling, 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 utilisation. It started out as a method of wastewater disposal for environmental reasons, but is now also being used to counteract pressure draw-down, i.e. as artificial water recharge, and to extract more of thermal energy in 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

We conclude this paper by discussing two case studies related to sustainable management. One of these 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 other 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 latter resource is of an entirely different nature, and requires full reinjection for sustainable utilisation, as well as common management, to avoid overexploitation.

### 4.1 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 Dalvík since 1969. Two production wells, with feed-zones between depths of 500 and

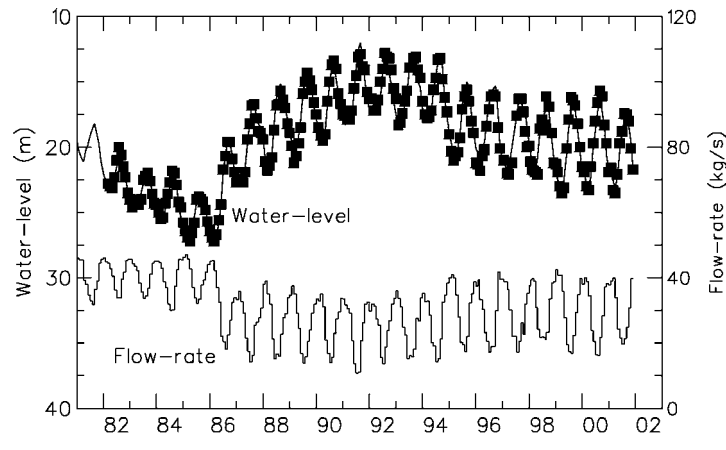
800 m, in the basaltic lava-pile, are currently in use and the reservoir temperature is about 65°C. The average yearly production from the Hamar system has varied between 23 and 42 l/s, and the total production during the 33-year utilisation history has amounted to 32,000,000 m<sup>3</sup>. This production 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 world-wide (Axelsson and Gunnlaugsson, 2000).

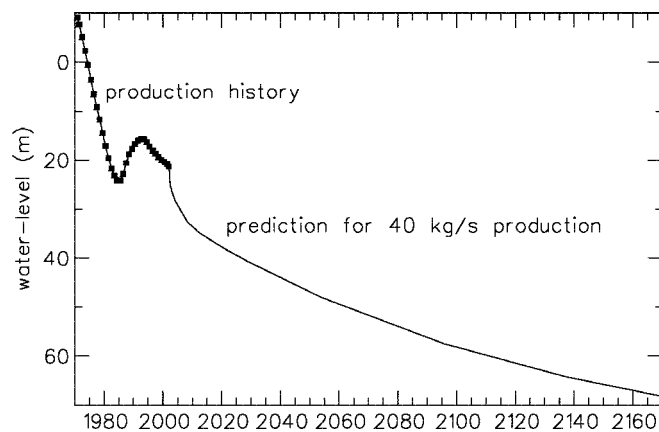
The Hamar system appears to have been utilised in a sustainable manner during the last three decades. The production history is too short, however, to establish whether the current level of utilisation is sustainable according to the definition in chapter 2 above. Therefore, the sustainable production 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 simulate (predict) the pressure changes (water level) in the Hamar geothermal system for a 200-year production history. The results are pre-sented 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  $\pm 30$  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 depths of 200-300 m.

The eventual temperature drawdown in the Hamar system, due to colder water inflow, 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



**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 waterlevel (pressure) changes in the Hamar geothermal system for a 200-year production history.**

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  $0.5 \text{ km}^3$ , 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 = $0.5 \text{ km}^3$	Volume = $1.0 \text{ km}^3$
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

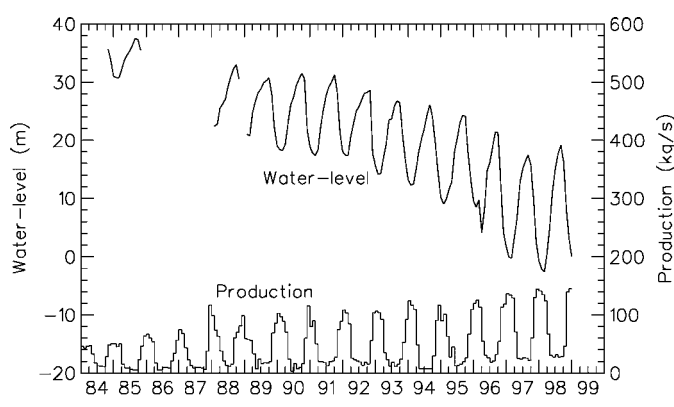
These results indicate that if we again assume a production history of the order of 200 years that it should be possible to maintain production of at least 40 kg/s for this period, assuming the conservative reservoir volume. It may also be mentioned that it only takes about 15-45 years to replace the water in-place 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  $>40 \text{ kg/s}$  and that  $E_0 > 11 \text{ MW}_{\text{th}}$  (assuming a reference temperature of  $0^\circ\text{C}$ ).

## 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 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. Discussion of sustainable management of the Beijing geothermal resources by Axelsson *et al.* (2002) is the basis for the following. 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 utilised since the 70's and 80's, respectively (Liu *et al.*, 2002). Plans are being made to increase geothermal utilisation in Beijing, in particular for space heating, in order to help battle the serious 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



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

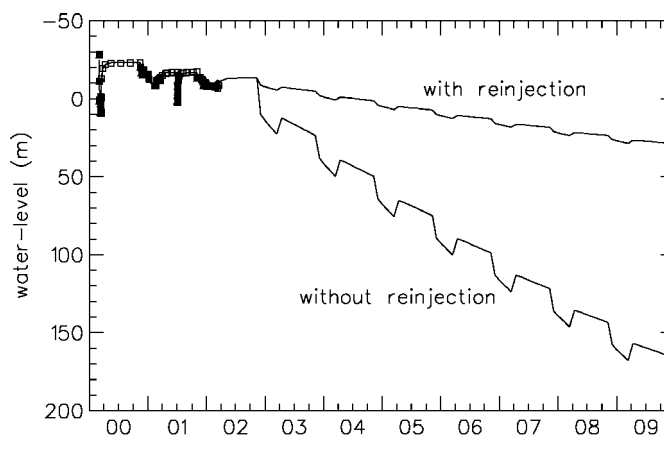
production remaining relatively constant (see Figure 6). This clearly indicates that the underlying reservoirs have limited recharge and, in fact, act as nearly closed hydrological systems.

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<sup>2</sup> (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 utilised for three years now with a careful monitoring program in place, and lumped parameter model has been used to simulate the data collected (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, waterlevel drawdown may be expected in the reservoir.

Predictions with reinjection show that reinjection will be essential for sustainable utilisation of this reservoir. Without reinjection its potential appears to be quite limited. The Shahe reservoir suffers, in fact, from a lack of water. 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 artificial recharge.

These results clearly indicate that reinjection will be essential if plans for increased use of the geothermal resources in Beijing are to materialise 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.

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 common management of the geothermal resources, because many different users may be utilising 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, utilisation of different wells, in different areas, needs to be carefully harmonised.



**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.**

## 5 Concluding remarks

To conclude, the following should be emphasised: Sustainable geothermal utilisation 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 utilise the same resource, without common management. Energy-efficient utilisation, as well as careful monitoring and modelling, are essential ingredients in sustainable management. Reinjection is also essential for sustainable utilisation 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 each 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<sub>th</sub>.

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, re-injection is a prerequisite for their sustainable utilisation. Common management, to harmonise the production by different users, and minimise interference, is also essential, as well as energy-efficient utilisation.

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