SUSTAINABLE BENEFITS OF GEOTHERMAL UTILIZATION

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KEY WORDS

Sustainable utilization, renewable energy source, definitions, reinjection

ABSTRACT

Geothermal energy is a renewable energy source that can be utilized in a sustainable way. The geothermal energy source is a dynamic feature within the crust of the Earth, which means that mining classifications like reserves, resources, and resource base are not applicable to geothermal energy. For each geothermal system and for each mode of production there exist a certain limit for sustainable production. Sustainable geothermal utilization involves energy production that can be maintained for a very long time. This requires efficient management in order to avoid overexploitation. Energy-efficient utilization, reinjection, as well as careful monitoring and modeling are essential ingredients in sustainable management. The limiting factors of the sustainable potential of a given geothermal resource are either the flow of energy or the flow of fluid to the geothermal reservoir.

1. INTRODUCTION

Geothermal energy is a renewable energy resource that can be utilized in a sustainable manner. Unfortunately, there seems to be some confusion about the meaning of the expressions *renewable* and *sustainable*, and these issues are in some cases mixed up in the discussion of energy resources. The purpose of this paper is to present detailed definitions of these concepts and to underline that the concepts renewable and sustainable are not comparable. *Renewable* describes the property of an energy resource whereas *sustainable* refers to the utilization mode through which the energy from the resource is harnessed.

It is highly important that the discussion on geothermal energy is based on a firm scientific basis, and to avoid misconceptions influencing our judgment of the different energy resources. According to an estimate presented in the *World Energy Assessment* [1], the technical potential of geothermal resources

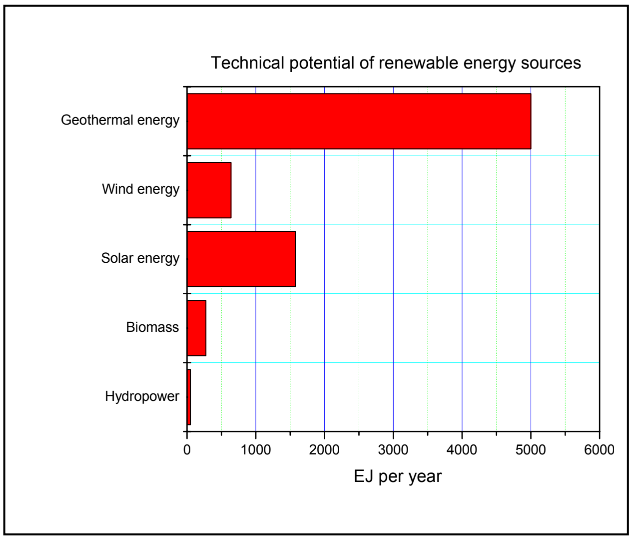

Figure 1: Technical potential of renewable energy sources. Data from [1] .

is greater than that of other renewable energy sources, see Figure 1. In the process of replacing fossil fuels with renewable energy sources, geothermal energy is, therefore, bound to play a major role.

2. FINITE AND RENEWABLE RESOURCES

Most of the resources in the crust of the earth, like metals and hydrocarbons, are finite in the sense that the total amount of metals or hydrocarbons is of a finite size at a fixed location. Mining of the metals is carried out in mines where the concentration of the metal under consideration is higher than in other parts of the crust. When all the high-grade ore has been mined from a given mine, the mine is empty, at least from the financial point of view. This kind of resource is classified as a finite resource. It is possible to deplete the resource, and the resource will remain depleted.

The wind is blowing over the surface of the earth and it is possible to use windmills to transfer the kinetic energy of the wind into electricity or some other form of energy. By doing so, our utilization of the wind energy will hardly influence the strength of the wind. It is not possible to deplete the resource of wind energy by harnessing the wind energy in windmills. The wind will continue to blow in spite of our effort to extract energy out of this natural process. Therefore, wind energy is classified as a renewable energy source.

An important difference between the finite and the renewable resources in the crust and on the surface of the earth is that all finite resources are *site specific*, meaning that these resources have a specific location in the crust or on the surface of the earth, whereas the renewable resources are dynamic phenomena and it is only possible to define an approximate location for these resources. The high-grade gold vein in our a gold mine has a very specific location in the crust and the vein will be at this location for a very long time (forever on the human timescale). On the other hand, the wind is blowing over a large area of the surface of the earth, and hot geothermal water is moving around in the crust. These energy resources are dynamic in their nature and they are only approximately site specific. Biological resources like the fish stocks in the ocean are swimming around and the fish can be caught at different locations.

The mining industry has developed an extending scheme to define the meaning of expressions like reserves, resources, and resource base. This methodology is based on the assumption that the phenomena under consideration are stationary within the crust. As the renewable resources are not stationary (not site specific), it is not possible to use this methodology to classify renewable resources like geothermal energy or the fish stocks in the ocean. For the renewable resources, expressions like: potential, technical potential, and economic potential are used instead to describe the size of these resources and to underline the differences between renewable resources and finite resources.

3. DEFINITIONS

The meaning of the terms renewable energy source and sustainable use of an energy source can now be defined. Renewable energy sources are in one way or another linked to some continuous energy process in nature. The conditions must be such that the action of extracting energy from the natural process will not influence the process or energy circulation in nature. A simple definition of a renewable energy source can be as follows:

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

It could be argued that oil and gas are renewable on a geological time scale, but this time scale is so long in relation to the human time scale that there is a common agreement to classify oil and gas as finite energy sources. Furthermore, the term *sustainable production of geothermal energy from an individual geothermal system* can be defined in the following way [2]:

> *For each geothermal system, and for each mode of production, there exists a certain level of maximum energy production,* $\mathbf{E_0}$*, 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* $\mathbf{E_0}$ *it cannot be maintained for this length of time. Geothermal energy production below, or equal to* $\mathbf{E_0}$*, is termed* ***sustainable production,*** *while production greater than* $\mathbf{E_0}$ *is termed* ***excessive production.***

This definition does neither consider economical aspects, environmental issues, nor technological advances, all of which may be expected to fluctuate with the times. Furthermore, 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 $\mathbf{E_0}$ is not known a priori, but it may be estimated on the basis of available data (by modelling). Figure 2 presents a schematic drawing illustrating the difference between sustainable and excessive production.

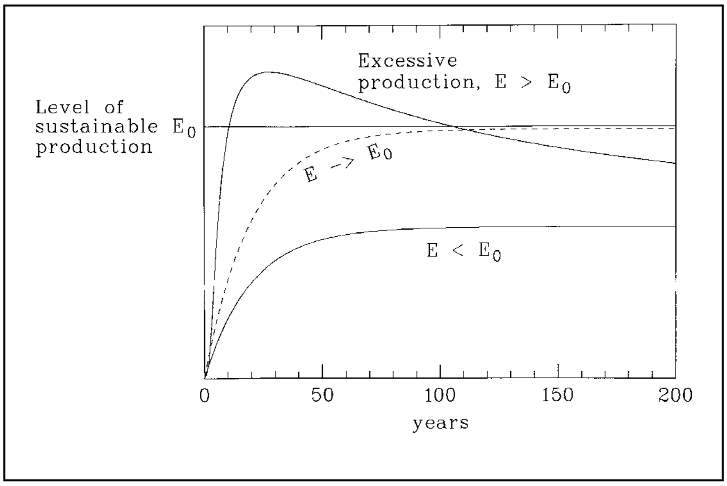

Figure 2. A schematic figure illustrating the difference between sustainable and excessive production. From [2].

4. RENEWABLE ENERGY SOURCES

Strictly speaking, it is only the time scale that divides the energy resources into renewable resources and finite resources. Human time scale is used as reference for this purpose. It is known that hydrocarbon reservoirs are formed in the crust in a time span of some 50-100 million years, but this time is so long compared to the time scale used by human beings that the maturation of hydrocarbon reservoirs is defined as not renewable on the time scale of the activities carried out by mankind. It is possible to extract the energy from a hydrocarbon reservoir in a time that is a million times shorter than the time required to form the resource.

Also, it can be argued that the natural processes that are the basis for renewable energy resources are finite, if a very long time scale is considered. Most of the renewable energy resources like solar, wind, and hydro depend on the energy radiation from the sun. The lifetime of the sun is, however, limited even though this time is even longer than the geological time needed for the formation of oil reservoirs. Furthermore, it can be argued that the thermal energy of the interior of the earth is also of finite size causing geothermal energy also to be a finite resource, if a very long time is considered.

The requirement that the human time scale should be used as the reference point in the definition of renewable versus non-renewable energy resources can create some gray areas, where it might not be clear if the resource should be classified as renewable or non-renewable. Geothermal energy is an example where such ambiguity can be noted.

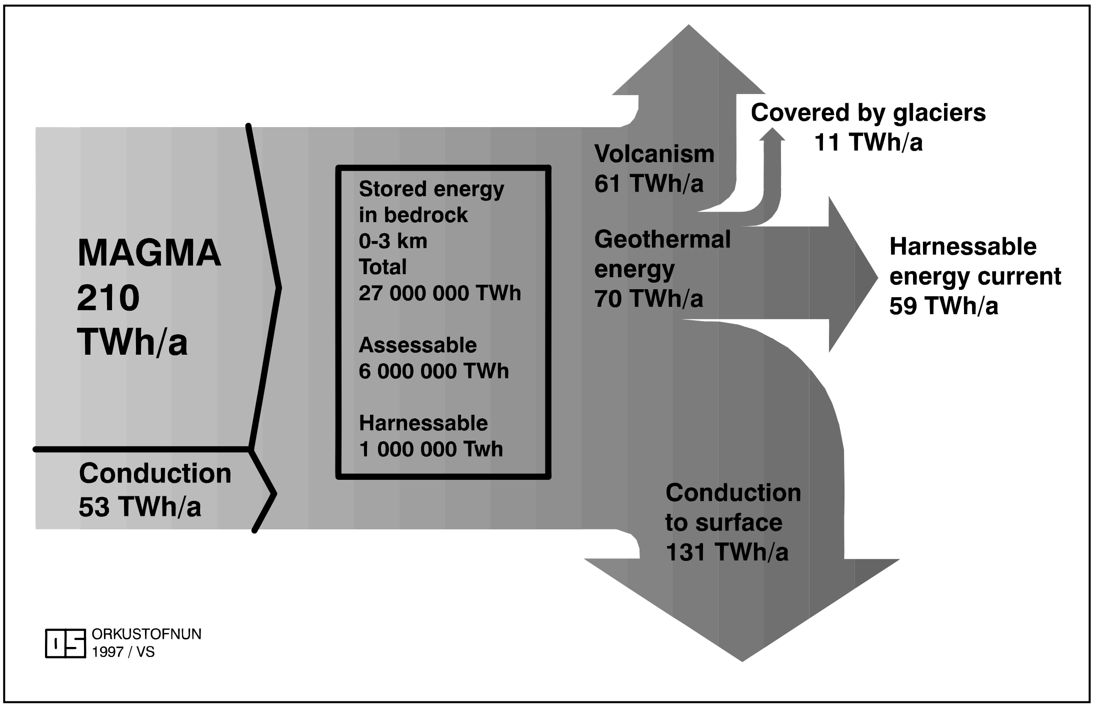

Figure 3. The terrestrial energy current in Iceland. From [3].

The reason for the apparent ambiguity depends on the different mode of energy transport within the crust. It is instructive to consider the current of geothermal energy within the crust of Iceland as an example. The size of the terrestrial energy current in Iceland is schematically shown in Figure 3. The time constant used for the current in the figure is one year. The energy current from the interior of the earth is the primary source of geothermal energy in Iceland as shown in Figure 3.

The energy transport within the crust takes place by three processes:

- Advection of magma.
- Advection of geothermal fluid.
- Thermal conduction.

The transport of energy from the mantle is taking place simultaneously through all three processes, and the relative contribution of each transport mode is also changing from one place to another in the crust. Energy (heat) transport with the advection of magma and thermal water is a relatively fast process. Time constants in the range of days or months are suitable to describe these processes. On the other hand, thermal conduction is a relatively slow process where a time constant of the order of hundreds of years is needed to characterize the process. The utilization of geothermal energy from natural geothermal systems is primarily governed by the advection of thermal fluid in the crust.

If the energy transport is only by thermal conduction on the other hand, it is hardly possible to talk about "renewable" energy sources because the time constant of the energy replacement is much longer than the time constant required for the exploitation. All conventional exploitation of geothermal energy is based on energy extraction from natural geothermal systems where water transports the energy within and towards the systems, and water also transports the energy to the surface where the utilization takes place. Production causes a pressure decline in the geothermal system, which results in increased recharge of water and energy to the system under exploitation. These conditions are typical for renewable energy sources where the replacement of energy takes place on a similar time scale as the extraction.

The exception from this rule is hot dry rock and the extraction of connate water from some deep sediment. In the case of hot dry rock, the idea is to create an artificial geothermal system in impermeable rocks by injecting water in one well and extracting the heat stored in the rocks through another well. If the rock is completely impermeable, the replacement of energy to the reservoir will only take place as thermal conduction, and the replacement of the heat energy will take such a long time that it is questionable whether the resource can be classified as renewable in this case. Similar conditions might be present in sedimentary systems with no natural recharge. In most cases, however, there is some recharge to the sediments. Furthermore, the concept of hot dry rock is now changing rapidly to the concept of enhanced geothermal systems. For these enhanced systems, there is some natural recharge to the reservoirs, such that the energy recharge will partly take place through advection of thermal fluid and partly through thermal conduction. The question of renewability of the hot dry rock utilization mode will probably be of minor importance in the future.

It is interesting to note that the ambiguity of the renewability of geothermal energy results from the utilization mode applied. It might be possible to find cases where the definition of renewable energy source is hardly applicable. In all other cases, there is a common agreement that geothermal energy should be classified as a renewable energy source.

5. SUSTAINABLE USE OF ENERGY SOURCES

The term *sustainable development* became fashionable after the publication of the Brundtland report in 1987 [4]. 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 world's' 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 [5], [3], [6], [7]. 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.

A renewable resource can be harnessed (managed) both in a sustainable way and in a way that cannot be classified as sustainable. The use of geothermal energy is considered in this chapter in order to explain somewhat the concept of sustainable production of geothermal energy. Five examples from different parts of the world are discussed.

Matsukawa, Japan

The energy production potential, or capacity, of geothermal systems is highly variable. It is primarily determined by pressure decline due to production, but also by energy content. Pressure declines, for example, continuously with time in systems that are closed or with small recharge. Production potential is, therefore, often limited by lack of water rather than lack of energy. The nature of the geothermal systems is such that the effect of "small" production is so minor 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 not be maintained for long.

Several decades worth of experience has been accumulated on the production of geothermal energy in a number of geothermal areas, woldwide. In many cases, this experience has shown that by maintaining production below a certain limit, the geothermal system reaches a certain balance, which may be maintained for a long time.

The Matsukawa geothermal power station has continued successful power generation since 1966. The power plant has been operated so as to maximize the profit instead of insisting on operating continuously at full power [8]. However, the output from the reservoir has been fairly constant for more than 30 years, as shown in Figure 4. Matsukawa can be considered to be an example of sustainable geothermal development.

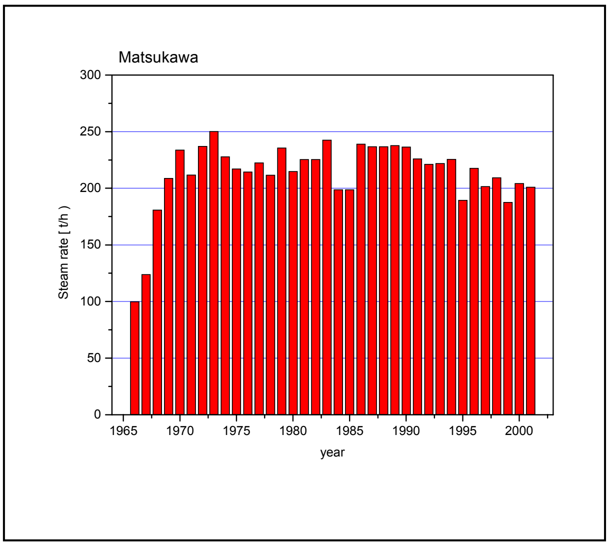

Figure 4. The production history of the Matsukawa geothermal field in Japan. Based on data in [8].

The Geysers, California

The development at The Geysers field in California can serve as an example where the production has been so great that an equilibrium was not attained. Twenty geothermal power plants, with a combined capacity of about 2,000 MW, were initially constructed in the field.

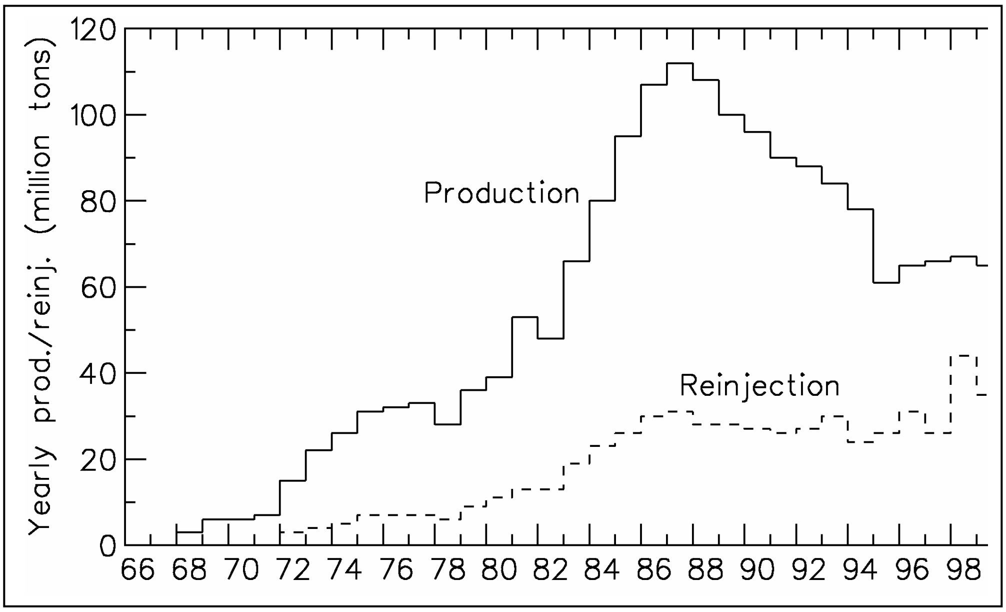

Figure 5. Production- and reinjection history of The Geysers geothermal field in California. [9].

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 5. The natural recharge to The Geysers field appears to limit the long-term production capacity of the field. In recent years, great efforts haves been put into increasing the volume of reinjected water into the field. This effort has been successful, and the leveling off in the production after 1995 is considered to be the effect of increased reinjection.

Laugarnes, Iceland

All production of geothermal energy in Iceland is from natural geothermal systems, and it should therefore be classified as utilization of a renewable energy source according to the description above. At present, there are about 200 geothermal systems (small and large) in use in the country [10]. The longest continuous exploitation time for a single system is 70 years for the Laugarnes area, situated within the city of Reykjavik. In none of these cases has the production been discontinued because the source was depleted. On the contrary, the experience is such that the geothermal systems appear to be able to sustain continuous production for such a long time, that it is appropriate to talk about sustainable exploitation. The production from the Laugarnes field is a good example of these conditions.

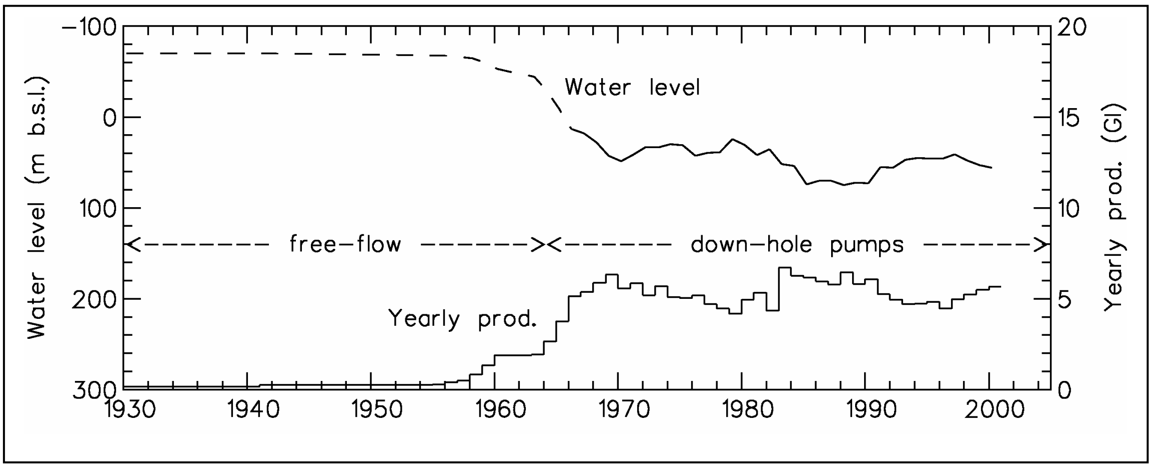

Figure 6: The production and water-level history of the Laugarnes geothermal system in SW-Iceland. From [11].

For the first 25 years of exploitation in the Laugarnes field, the production was only by free flow from wells, but submersible pumps were introduced in the late fifties. The new production method made it possible to increase the production ten times as shown in Figure 6. The response of the system was that the pressure (water level) fell but a new equilibrium state was reached where the water level was on the average 120 m below the initial level when the production started in the year 1930. The increased production from the field has not caused changes in the reservoir temperature. The geothermal system in Laugarnes is approximately in equilibrium for the 6 Gl/a (160 l/s) production, which has been maintained for the last 30 years. This means that the pressure decline has caused increased natural recharge and the rate of recharge is, on the average, the same as the rate of production from the system. It is quite obvious that the present production in Laugarnes field constitutes sustainable exploitation, and that the energy resource is renewable. Furthermore, it should be noted that the potential for sustainable production appears to be about ten times higher than the natural discharge from the field.

Hamar, Iceland

The Hamar geothermal field in Central N-Iceland is one of numerous low-temperature geothermal systems located outside the volcanic zone of the country. 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 [12]. 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 utilisation history has amounted to 32,000,000 m^3. 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 7 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 geo-thermal systems world-wide [12].

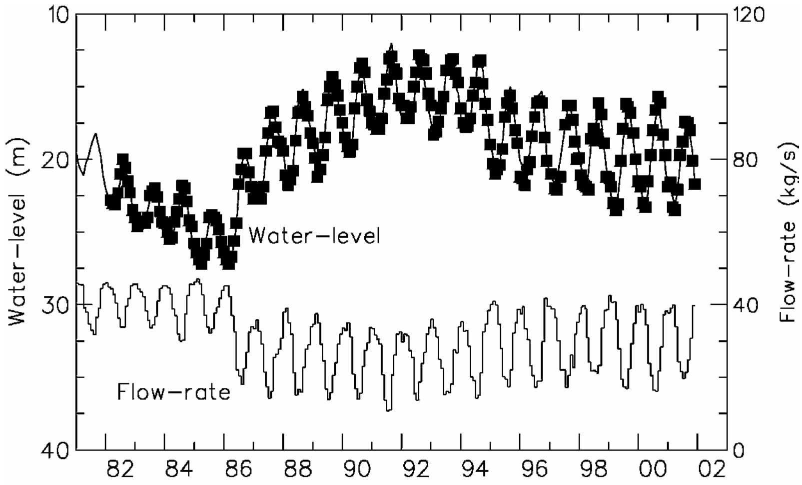

Figure 7: Last two decades of the production history of the Hamar geothermal system, the water-level history having been simulated by a lumped-parameter model (squares = measured data, line = simulated data). From [11].

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 in chapter 3 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 was used to simulate (predict) the pressure changes (water level) in the Hamar geothermal system for a 200-year production history. The results are presented in Figure 8 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 the system should be able to sustain more than 40 kg/s, with down-hole pumps at depths of 200-300 m.

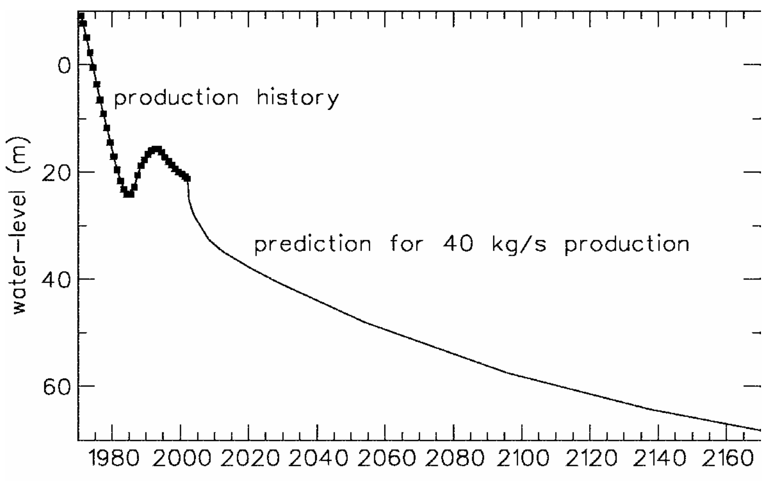

Figure 8: Predicted water-level (pressure) changes in the Hamar geothermal system for a 200-year production history. From [11].

The eventual temperature draw-down 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 [13]. 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 Table 1 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. From [11].

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

These results indicate that if a production history of the order of 200 years is again assumed it should be possible to maintain production of at least 40 kg/s for this period of time, assuming the conservative reservoir volume.

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). It can also be concluded that the sustainable rate of production is > 40 kg/s and that E_0 > 11 MW_{th} (assuming a reference temperature of 0°C).

Beijing, P.R. of China

Beijing City is situated on top of a large and deep sedimentary basin where geothermal resources have been found. 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. The following is based on a discussion of the sustainable management of the Beijing geothermal resources [11]. The reader is referred to that paper for more details.

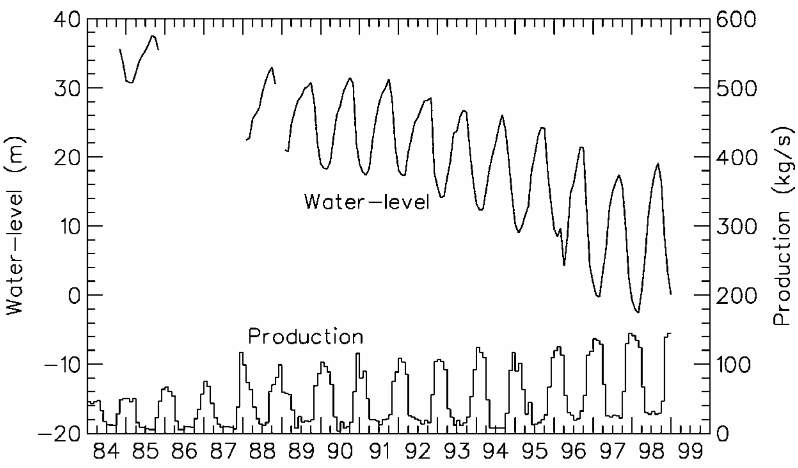

Figure 9: Part of the production and water-level history of the Xiaotangshan geothermal field in Beijing [11].

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 [14]. Plans are being made to increase geothermal utilization 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 production remaining relatively constant (see Figure. 9). 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 $100 km^2$ [15], [16]. 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.

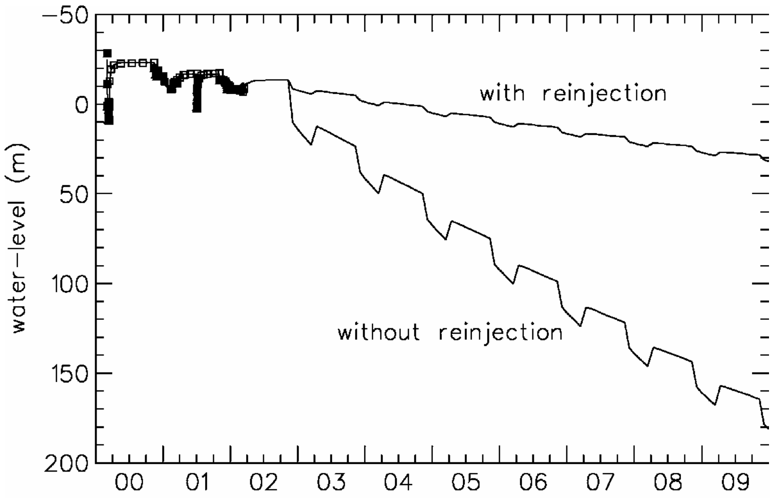

Figure 10: Results of modeling calculations for well ShaRe-6 in Beijing. Predictions for utilization scenarios with 80-90% reinjection and without reinjection are shown. From [11].

Well ShaRe-6 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 [11]. The results show clearly that the Shahe reservoir is an almost closed system (with limited recharge). Figure 10 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. 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 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.

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 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.

6. CONCLUDING REMARKS

Generating capacity of geothermal reservoirs is frequently quoted in feasibility reports. In such cases, it is estimated in one way or another that the geothermal reservoir will be able to withstand a given production for the same time as the estimated lifetime of the constructions and the utilization equipment used. Constructions might be depreciated in 30 years and the lifetime of the equipment and constructions might be some 50 years. Therefore, it is quite usual that the generating capacity of a geothermal resource is referred to 30 years. This is an economic estimate that should not be mixed up with sustainable utilization. In many cases, it might be more economical to squeeze as much energy as possible from the resource under the relatively short lifetime of the plant constructed rather than think of the sustainable potential of the resource. If such a development mode is adopted it should be noted, however, that the production from the resource will have to be reduced drastically or stopped after some 30-50 years, and the resource will have to be allowed to recover from the excessive production.

If the generating capacity of a geothermal resource is referred to as 200-300 years, we obtain more or less the sustainable potential, E_0, used in the definition of sustainable use. 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.

The long exploitation history of the Laugarnes field in Iceland shows that the potential for sustainable production from a field can be much larger than the natural discharge from the same field. 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_{th}.

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. In conclusion, it can be stated that the limiting factors of for the sustainable potential of a given geothermal resource are either the flow of energy or the flow of fluid to the reservoir.

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