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Sustainable use of geothermal resources: renewability aspects

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Abstract

The sustainable use of geothermal resources should secure longevity of production. This can be achieved by moderate production rates, taking into account the local conditions (field size, natural recharge rate, etc.). After production stops, the resources recover by natural processes; the production of geothermal fluid and/or heat successively creates a hydraulic/heat sink in the reservoir. This leads to pressure and temperature gradients which in turn – after termination of production – generate fluid/heat inflow to re-establish the pre-production state. The question of sustainability and renewal thus boils down to the rate of fluid/heat resupply. Unlike mining activities (although geothermal is often regulated in many countries by the mining law) where the mined-out ore is gone forever, the replenishment of geothermal resources always takes place, albeit at sometimes low rates. The recovery shows asymptotic behaviour, being strong at the beginning and slowing down subsequently, the original state being re-established theoretically only after infinite time. However, practical replenishment (e.g. 95% recovery) will already be reached much earlier, generally on a time-scale of the same order as the lifetime of geothermal production systems.

1 Introduction

In general, geothermal energy is labeled as renewable. It is, therefore, listed together with solar, wind and biomass alternative energy options in governmental R&D programs, in materials promoting geothermal energy. This attribute applies only with certain restrictions, which must be addressed in a fully objective manner.

The ultimate basis of geothermal energy is the immense heat store in the earth's interior. The total heat content can be estimated to be around 10^{31} J; it would take over 10^9 years to exhaust it by today's global terrestrial heat flow. A more restrictive estimate considers the surface area of continents (some $2*10^{14}$ m^2) and the continental crust to 1 km depth only. The heat content of this shell is still considerable, $3.9*10^8$ EJ. Taking into account the world's primary energy consumption, 400 EJ in 2000, this heat would be sufficient for a million years. Would this heat be extracted, it would need about 10^3 years to replenish the store by the terrestrial heat flow (Rybach et al., 2000). Thus the resource base is sufficiently large and is basically ubiquitous.

The original definition of sustainability goes back to the Bruntland Commission (1987; reinforced at the Rio 1991 and Kyoto 1997 Summits):

> *"Meeting the needs of the present generation without compromising the needs of future generations."*

In relation to geothermal resources and, especially, to their exploitation for geothermal energy utilization, sustainability means the ability of the production system applied to sustain the production level over long times. Sustainable production of geothermal energy therefore secures the longevity of the resource, at a lower production level. A definition of sustainable production from an individual geothermal system has been suggested recently (Orkustofnun Working Group, 2001):

> *"For each geothermal system, and for each mode of production, there exists a certain level of maximum energy production, below which it will be possible to maintain constant energy production from the system for a very long time (100 – 300 years)."*

The definition applies to the total extractable energy (= the heat in the fluid as well as in the rock), and depends on the nature of the system but not on load factors or utilization efficiency. The definition does not consider economic aspects, environmental issues or technological advances, all of which may be expected to change with time.

The terms renewable and sustainable are often confused; the former concerns the nature of a resource and the latter applies to how a resource is utilized (Axelsson et al., 2002). In the following, the effects of heat/fluid production from a geothermal reservoir will be described.

2 Effects of heat/fluid production from a geothermal reservoir

The customary use of geothermal resources is established by withdrawing the fluid and extracting its heat content. There are prominent examples that this can happen in a fully renewable fashion: thermal springs in many parts of the world have been conveying impressive amounts of heat (and fluid) to the surface for centuries, without showing any signs of a decline. In such situations, obviously a balance exists between surface discharge and fluid/heat recharge at depth. Any "balanced" fluid/heat production by a geothermal utilisation scheme, i.e. which does not produce more than the natural recharge resupplies, can be considered as fully renewable (Stefansson, 2000). Such production rates are, however, limited and in many cases not economical. Often, the resources are taken into forced production (with the reservoir fluid as the heat carrier), mainly to meet economic goals like a quick pay-back of investments for exploration and equipment, in such a way that reservoir depletion is the result. There are numerous examples of this approach worldwide, the most prominent is the vapour-dominated field of The Geysers/USA. Figure 1 shows the effect of fluid production at the Calistoga Field.

Intensified production rates exceed the rate of recharge and lead with increasing production duration to depletion, especially of the fluid content, whereas the heat stored in the matrix remains, to a large extent, in place. Many utilisation schemes therefore apply reinjection (high enthalpy steam and/or water dominated reservoirs, doublets in hydrothermal aquifers), which at least replenishes the fluid content and helps to sustain or restore reservoir pressure. On the other hand, cold reinjected fluid creates thermal depletion in an increasing volume of the reservoir.

This is the bad news; but there is also good news: The production of geothermal fluid and/or heat successively creates a hydraulic/heat sink in the reservoir. This leads to pressure and temperature gradients which in turn – after termination of production – generate fluid/heat inflow to re-establish the pre-production state. The question of sustainability and renewal thus boils down to the rate of fluid/heat resupply. Unlike mining activities (although geothermal is often regulated in many countries by the mining law) where the mined-out ore is gone forever, the replenishment of geothermal resources always takes place, albeit at sometimes low rates.

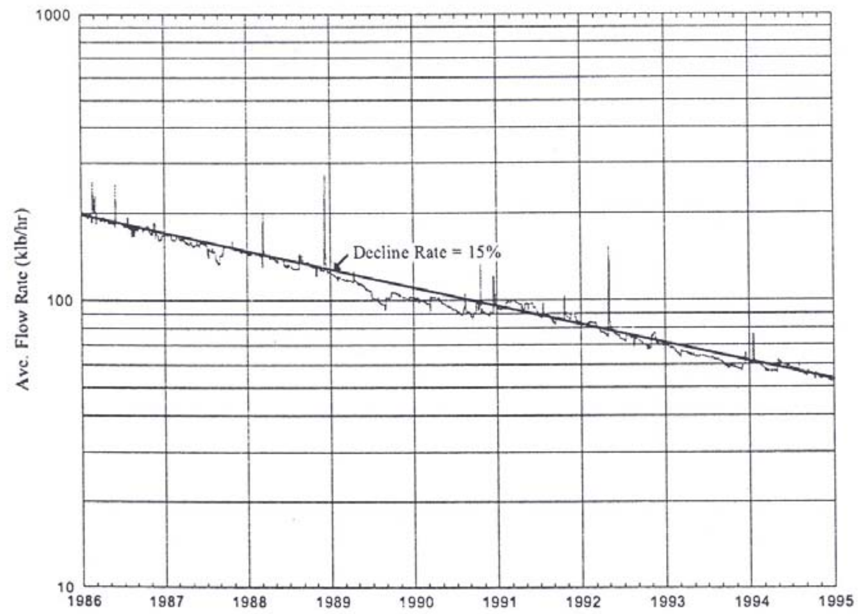

Figure 1: 150% production decrease over 10 years, Calistoga/The Geysers (USA) steam reservoir - average daily flowrate versus time. From Sanyal et al., 2000.

In the following, the sustainability aspects of various geothermal utilizations schemes will be addressed, with focus on the time-scale of recovery. Concerning the time scales of pre-production state re-establishment, three resource types and utilisation schemes will be treated: 1) heat extraction by geothermal heat pumps; 2) hydrothermal aquifer, used by a doublet system for space heating; 3) high enthalpy, two-phase reservoir, tapped to generate electricity.

3 Geothermal Heat Pumps (GHP)

In the case of GHPs, the issue of sustainability concerns the various heat sources. In the horizontal systems, the heat exchanger pipes are buried at shallow depth; the longevity of their smooth operation is guaranteed by the constant heat supply from the atmosphere by solar radiation. In the case of combined heating/cooling by GHPs, the heat balance (in/out) is given by the system design itself: replacement of heat extracted in winter by heat storage in summer. In the case of groundwater-coupled GHPs, the resupply of fluid is secured by the hydrologic cycle (infiltration of precipitation) and the heat comes either “from above” (atmosphere) and/or “from below” (geothermal heat flow); the relative proportions depend on aquifer depth. This leads to a ± constant aquifer temperature all over the year without any significant seasonal variation. Any deficit created by heat/fluid extraction is replenished by the (lateral) groundwater flow.

The situation with BHE-coupled GHP systems is different. During heat extraction operation, the BHE (borehole heat exchanger) evolves more and more to a heat sink. False design, especially with forced extraction rates (several tens of W per meter BHE length, in low thermal conductivity materials like dry gravel) can lead to freezing of the surrounding ground and thus to system collapse. Therefore the conditions need to be established by which a reliable operation can be secured also on the long-term (i.e. sustainable operation). Several such attempts have been published in the literature; one of the first such studies, rather complete, and supported by theory and experiments, will be summarized below.

3.1 GHP sustainability with borehole heat exchanger (BHE)

The question of sustainability of GHPs in general, and of BHE coupled HPs boils down to the question: For how long can such systems operate without a significant draw-down in production, i.e. reaching a level which is beyond economic viability? Therefore, the long-term production behavior of BHE-based GHPs needs to be addressed.

The oldest BHE installations are not older than about 15-20 years, thus experience and especially detailed studies on long-term performance (decades) are lacking. Therefore, the question arises about the reliability of such systems over the long run. Along the same line come the questions: Can such systems operate in a sustainable manner? Is the shallow geothermal resource renewable? Does the ground recover thermally after shut-down of the BHE heat extraction operation, which is customarily designed to run over a few decades?

To answer these questions, a combined theoretical/experimental approach has been followed to establish a solid, verified base for the confirmation of reliable long-term performance on one hand, and to clarify the terms of renewability on the other (Rybach and Eugster, 2002).

3.2 Study of long-term performance

The verified base to confirm the reliability of BHE/HP systems over the long-term has been elaborated by combining field measurements with numerical model simulations. For this basic study, a single BHE was treated. The approach used is described in detail in Eugster and Rybach (2000).

An extensive measurement campaign has been performed at a commercially installed BHE system in Elgg near Zurich, Switzerland. The object of the study is a single, coaxial, 105 m long BHE, in use since its installation (1986) in a single family house. The BHE stands isolated and supplies a peak thermal power of about 70 W per m length. By this, the BHE is rather heavily loaded. Thus the installation is by no means a particularly favorable example.

The aim of the measurement campaign is the acquisition of ground temperature data in the surroundings of the BHE as well as of operational parameters of the entire system. For this purpose, 105 m long measuring probes were installed in parallel boreholes at 0.5 and 1.0 m distances from the BHE, backfilled with a bentonite/cement mixture like the BHE itself. Both boreholes had been equipped in 1986 with buried temperature sensors at 1, 2, 5, 10, 20, 35, 50, 65, 85, and 105 m depths. The use of pre-aged Pt100 sensors, in combination with a high-resolution multimeter (DATRON 1061 A), provides maximum long-term stability (± 0.1°K accuracy, ± 0.001°K precision) over the entire measurement period. In addition to the ground temperatures, the atmospheric temperature variations and all parameters relevant to the operation for the entire system (hydraulic system flow rates, circuit temperatures, power consumption of the HP etc.) have also been recorded in 30 minute intervals.

These measurements represent a unique data base which in turn was used to validate a numerical model. For this, the results of the first measurement campaign (1986-1991) were used to calibrate a 2D numerical code (COSOND, in cylindrical coordinates; Eugster, 1991). The code treats diffusive heat transfer in the ground, advection in the BHE, heat transfer between the BHE fluid and the wall materials, as well as heat transfer between atmosphere and ground. The program flow is controlled by a load profile which contains the atmospheric temperatures and the operational data of the heat pump. Details are given in Gilby and Hopkirk (1985), and Eugster (1991). First, the temperature curve measured in September 1996 was "predicted" by simulation and in turn compared with the measured curve. The agreement was excellent; the deviations were within measurement error (± 0.1°K, see Rybach and Eugster, 1998). The excellent agreement between measured and calculated time histories at a number of specific points in the underground gives confidence to extrapolate future trends and situations by modelling.

These computer simulations have now been recalculated using an adapted load profile based on the atmospheric temperatures of the years 1991-1997 actually measured in the meantime at a nearby meteorological station (Tänikon/TG) as well as on the homeowner's records about heat pump operation times. The model grid had 11,700 grid cells in a model volume of $2x10^6$ m^3 (for details see Eugster and Rybach, 2000). The operation of the Elgg BHE plant has been further extrapolated for an additional 19 years to a final period of 30 years (1986 - 2015) - see Figure 2. The load profiles for these simulation runs are based on the new Swiss Standard Climatic Database (METEONORM, 1997).

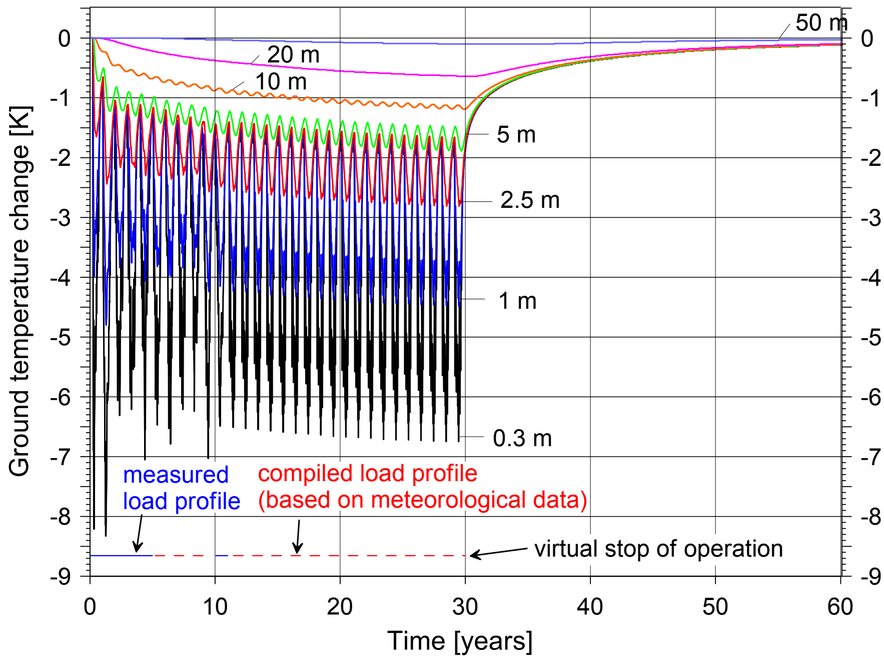

Figure 2: Simulated ground temperature changes of the BHE at Elgg relative to the starting, undisturbed situation in December 1986 over 30 years of operation and 30 years of recovery. From Rybach and Eugster (2002).

The complex thermal conditions around a BHE can also be addressed through numerical simulations. These are discussed in some detail below.

3.3 Thermal conditions around a BHE

Several superimposed processes govern the transient thermal conditions around a BHE in operation:

- A heavy cooling-down and a subsequent rewarming of the immediate vicinity of the BHE up to some 10 cm during an operational cycle (hourly cycle).
- The dissemination of this cooling and rewarming period up to several meters as a funnel-like temperature effect during a seasonal operation (yearly cycle).
- A large-scale, but only minimal cooling-down of the surrounding underground up to a distance of several 10's of meters during the full life cycle of the BHE (30-year-cycle).
- Both the horizontal and vertical heat fluxes increase around the BHE. The massive cooling down of the BHE vicinity enlarges the heat flows from the atmosphere and from the underground.

These pure conductive processes are rather complicated and are visualized in Figure 3 (also the result of the numerical simulation). But in free nature, flowing groundwater and - in saturated formations - water vapor diffusion processes add their effects to this complex system.

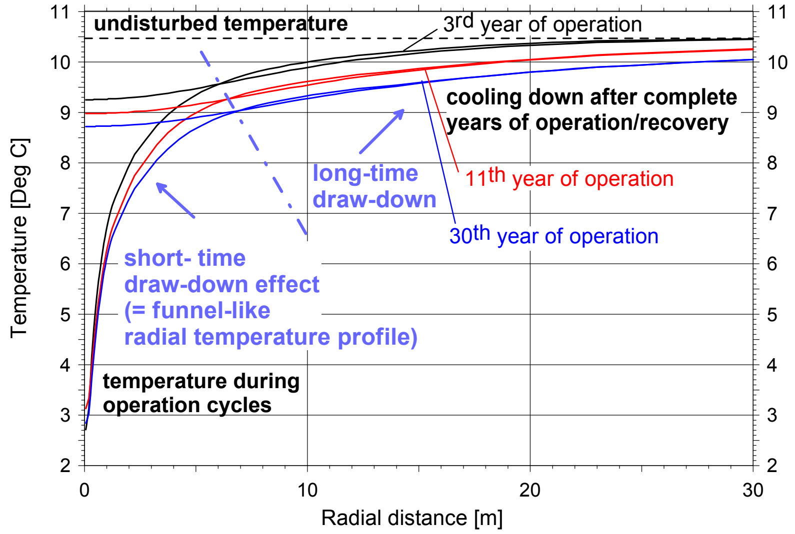

Figure 3: Funnel-like temperature distribution and long-term cooling-down around a BHE. The short-term and the long-term influences are well documented. From Rybach and Eugster (2002).

The operating BHE creates a heat sink in the ground which has a cylindrical shape. The isotherms are, after a certain operational time, concentrated near the BHE. For details see Eugster and Rybach (2000).

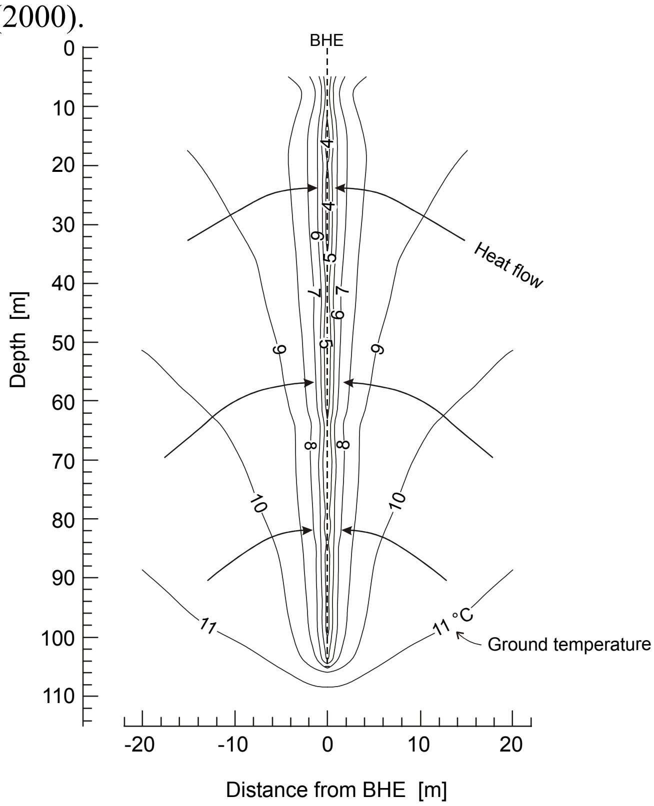

Figure 4: Calculated temperature isolines around a 105 m deep BHE, during the coldest period of the heating season 1997 in Elgg/ZH, Switzerland. The radial heat flow in the BHE vicinity is around 3 W/m^2. From Rybach and Eugster (2002).

The pronounced heat sink forms a cigar-shaped isotherm pattern, with the BHE as its center - see Figure 4). The heat sink creates strong temperature gradients in the BHE vicinity which in turn leads to heat inflow, directed radially towards the BHE, to replenish the deficit created by the heat extraction. This heat flow density attains, compared to the terrestrial heat flow (80 – 100 mW/m^2), rather high values (up to several W/m^2 - see Figure 4).

3.4 Thermal recovery

The long-term behavior of the single BHE-HP system was further investigated by numerical modelling. The results of the simulation runs show on one hand the expected decrease of the yearly temperature deficit, and on the other hand an increasing volume around the BHE which is affected by the cooling (see Figures 2 and 3).

After shut-down of heat extraction, regeneration of the ground begins. During the production period of a BHE, the draw-down of the temperature around the BHE is strong during the first few years of operation (see Figure 5). Later, the yearly deficit decreases asymptotically.

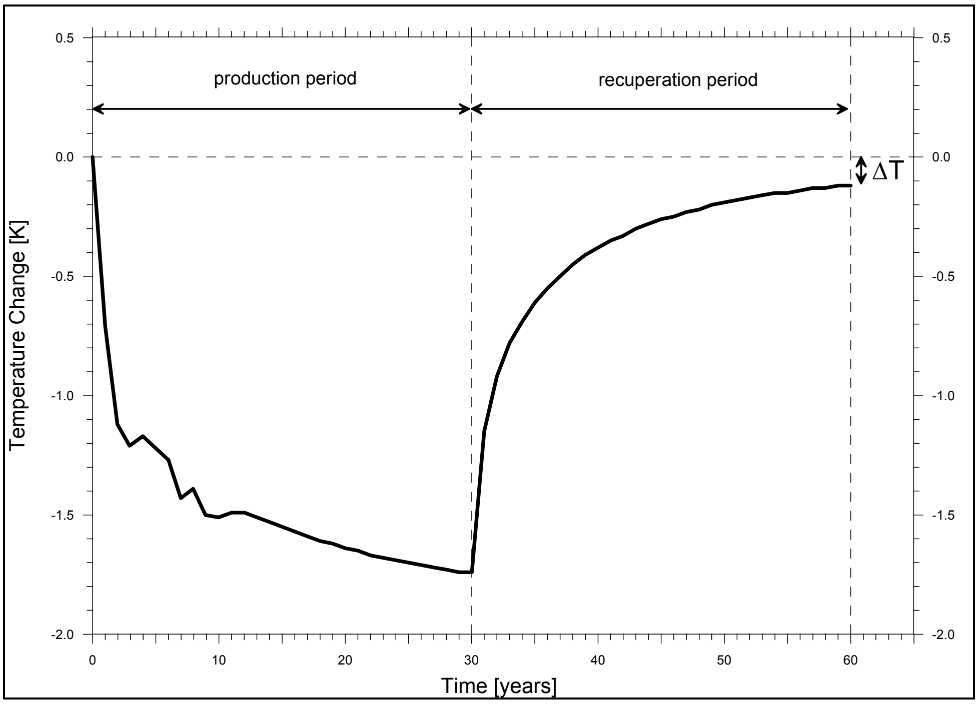

Figure 5: Calculated temperature change at a depth of 50 m and at a distance of 1 m from the BHE over a production period and a recuperation period of 30 years each. From Eugster and Rybach (2000).

During the recovery period after the stop of operation (assumed to happen after 30 years of operation), the ground temperature shows a similar behavior: during the first years, the temperature increase is strong, but tends with increasing recovery time asymptotically towards zero (Eugster and Rybach, 2000). The time to reach nearly complete recovery depends on how long the BHE has been operational. Principally, the recovery period equals the operation period. This is shown in Figure 6 for different distances from the BHE and for different final temperature deficits.

In summary, the measurements and model simulations prove that sustainable heat extraction can be achieved with such systems. The installation in Elgg supplies on the average about 13 MWh per year. In fact, the BHE's show stable and reliable performance which can be considered renewable. Reliable, long-term performance provides a solid base for problem-free application; correct dimensioning of BHE gives great scope of widespread use and optimization.

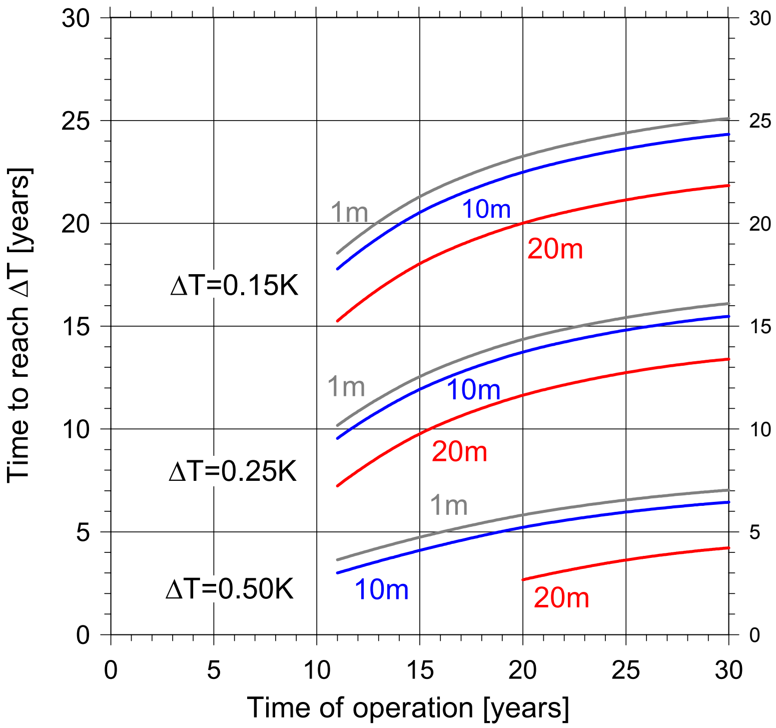

Figure 6: Duration of recovery period to reach a minimal final temperature deficit (ΔT) of 0.5, 0.25, and 0.15°K for different distances from the BHE as a function of the time of operation. From Rybach and Eusgter (2002).

Sustainability aspects of GHP systems have been addressed above, with emphasis on Borehole Heat Exchanger (BHE)/Heat Pump (HP) systems. They prove to be a feasible way to tap shallow geothermal resources which, located directly below our feet, represent a unique, ubiquitous and therefore enormous geothermal potential. They operate reliably also over the long-term. The results of numerical modelling for a single BHE show that the long-term performance of the BHE/HP system stabilizes, relative to initial conditions, at a somewhat lower but quasi-steady level after the first few years. Thus, sustainable operation can be achieved.

The basic studies about long-term performance presented here apply to a single BHE. Similar studies are underway for BHE groups/patterns.

4 Hydrothermal aquifer

The heat content of a deep aquifer can be utilised by producing the aquifer's fluid. The fluid's heat is transferred through a heat exchanger to a district heating network (often via a heat pump), whereas the cooled water is reinjected into the aquifer by a second borehole at a sufficient distance to the production borehole (doublet operation). Due to this geothermal circuit, the produced hot fluid is continuously replaced by cooled injected water. This leads to an increasing volume of thermal drawdown propagating from the injection to the production well. After the thermal breakthrough time, the temperature of the produced fluid will decrease with a rate depending on the production rate, the distance between the boreholes, as well as on the physical and geometric properties of the reservoir. The increasing thermal gradients in the reservoir cause a corresponding increase in conductive thermal recovery. Hence, a thermal steady state will be reached after a sufficient circulation time, which yields a practically constant production temperature; the production at that rate can further be sustained.

The town of Riehen next to Basel has the first and so far only geothermal based district heating system in Switzerland, with a capacity of 15 MW_t, which supplies about 160 users. About 50% of the needed energy is covered by a geothermal doublet operation (production well 1,547 m, reinjection well 1,247 m at a distance of 1.0 km). The fluid is produced/reinjected from/to a fractured aquifer (Triassic "Oberer Muschelkalk" - see Figure 7). The average flow rate is 10 l/s, at 62°C. Reinjection temperature is 25°C which yields a useable temperature drop of 37°K. The use of geothermal energy and the heat pump started operation in 1994. Since 1998, an extension into the neighbouring German town of Lörrach has been established.

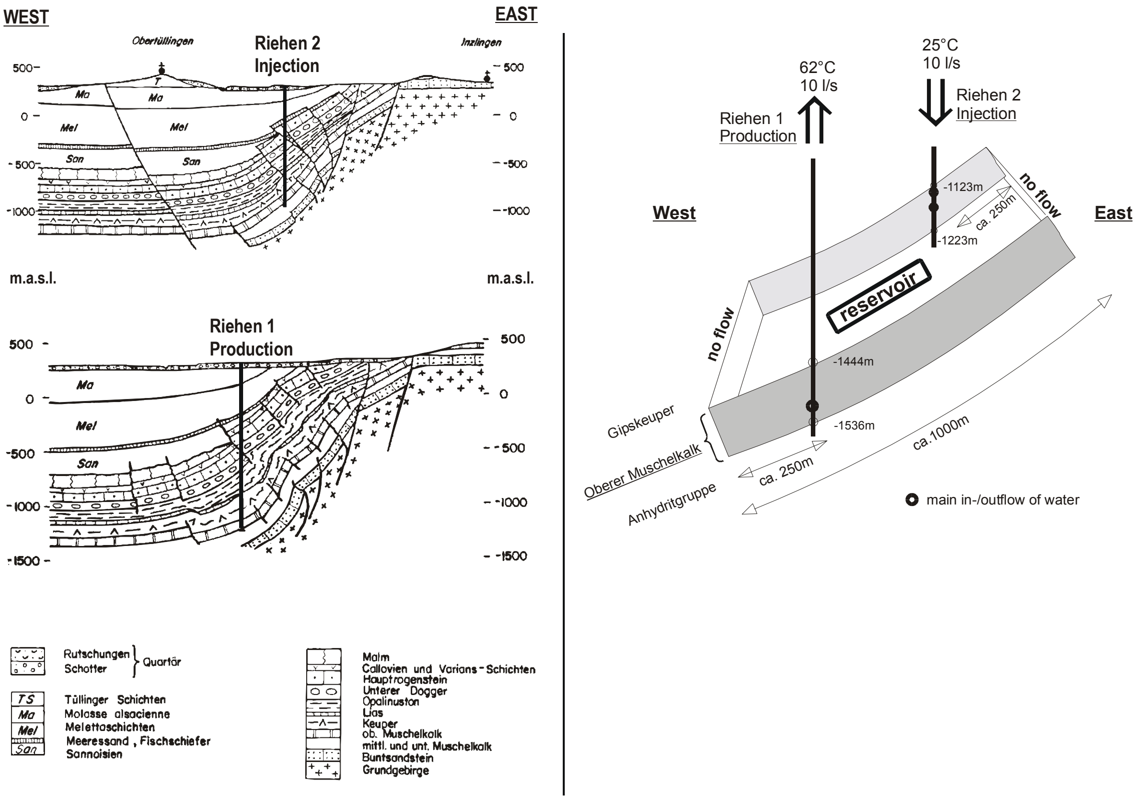

Figure 7: Geological cross-section and conceptual model of the aquifer of the doublet operation in Riehen. From Mégel and Rybach (2000).

For this system, it is essential to provide the heat exchanger with a production temperature of 62°C without a considerable drawdown for about 30 years. It has been demonstrated by numerical (finite element) calculations that these boundary conditions are fulfilled by the geothermal circuit. The numerical simulations have been performed with the FE-code FRACTure (Kohl, 1992; for details about the site see Mégel, 1996).

Additional attention is focussed on the recovery effect of the geothermal doublet operation in Riehen. Numerical simulations for porous and fractured reservoir models have been performed, for production and production break phases of different duration (10, 20, 40 years). Three different FE models have been used for the calculations of the production temperature and thermal recovery: 1) homogeneous porous aquifer; 2) fractured aquifer with a distance between the fracture zones of 50 m; 3) fractured aquifer with a distance between the fracture zones of 100 m. For details see Mégel and Rybach (2000).

For the Riehen doublet operation, a long-term calculation has been carried out with the 100 m spaced fracture zone model. The steady state production temperature is not reached even after 300 years (Figure 8). The development of the temperature can be characterised by considering the temperature change ΔT over a given time period, e.g. 10 years. This curve indicates the asymptotic behaviour of the production temperature. The maximum value of -0.7°K/10 years is obtained after 20 years; afterwards the temperature drop decreases down to a value of -0.15°K/10 years after 300 years production. Thus practically constant heat production can be sustained.

Table 1: Circulation scheme dependent recovery of the reservoir (see Figure 9). From Mégel and Rybach (2000).

Circulation scheme	Circulation rate [l/s]	Considered time period [years]	Energy production [MWh]	Energy production [%]	Reservoir recovery [%]
1x80 year production -recovery cycle, no thermal drawdown	10	160	1,089,043	105.5	100
no production breaks	5	160	1,071,908	103.8	70
8x10 year prod.-rec. cycles	10	160	1,059,875	102.7	48.7
4x20 year prod.-rec. cycles	10	160	1,052,908	102.0	36.5
2x40 year prod.-rec. cycles	10	160	1,043,995	101.1	20.8
1x80 year prod.-rec. cycle	10	160	1,032,164	100	0

The thermal recovery of the reservoir can be expressed by the comparison of the extracted energy decrease between the first and the second production phase with and without a production break between the two phases (Pritchett, 1998). A comparison between the production temperature of production-recovery cycles of 10, 20 and 40 years shows that the temperature will remain on a level which is higher the shorter the cycle period is (Figure 9). Relating the energy production of the most ideal case of no thermal drawdown to the energy output of a constant-rate production with a continuous temperature drop, the thermal recovery for an operating scheme with 10 year production-recovery cycles over 160 years amounts to 48.7% (Table 1). For cycles of 20 years, the corresponding value is 36.5%; for 40 years 20.8% respectively.

Consequently, short production-recovery cycles produce more energy and are therefore more favourable with regard to the geothermal energy utilisation. Sustainable heat production can be maintained over decades; for details see Mégel and Rybach (2000).

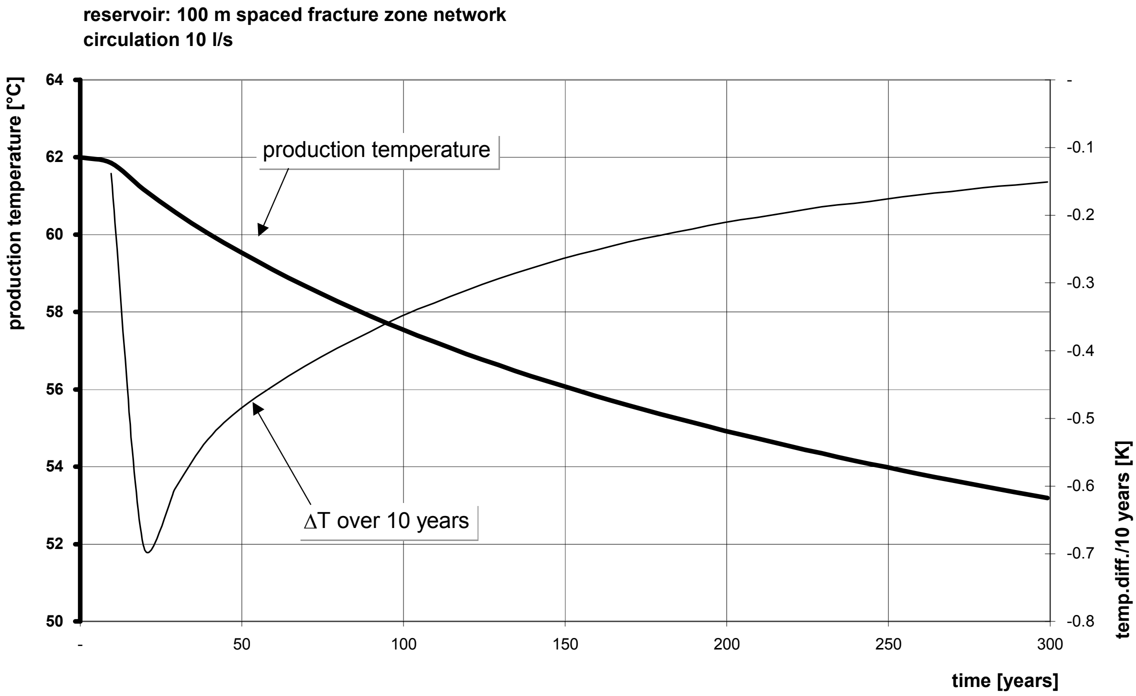

Figure 8: Development of the production temperature for a 100 m spaced fracture zone reservoir model (see also Figure 7). From Mégel and Rybach (2000).

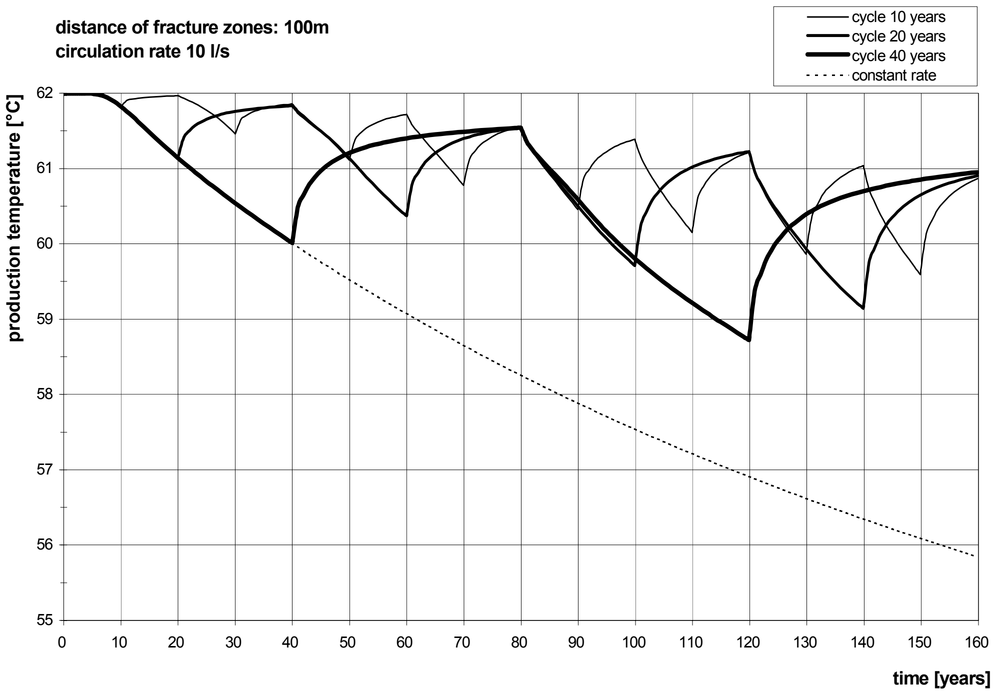

Figure 9: Production temperature for production-recovery cycles of different duration in a doublet operation. From Mégel and Rybach (2000).

5 High-enthalpy two-phase reservoir

Resources of this type are widely used to generate electricity. Some of them show strong signs of depletion. Therefore, reinjection schemes are increasingly introduced. Reinjection however can cause temperature decrease in the resource volume; together with the production rates dictated by economic constraints rather then by balancing the natural resupply. This can limit the productive lifetime of power plants to a couple of decades only.

A thorough theoretical study on the electrical production capacity of a hypothetical reservoir, albeit with realistic operational characteristics, has been presented by Pritchett (1998), for a certain ratio of production/natural recharge ratio. Of course, this ratio can vary strongly, according to local conditions. The study addresses the changes in electricity generating capacity in time, first during ongoing (continuous) two-phase fluid production, and subsequently the recovery after shut-down of the power plant operation.

Figure 10 shows the results of Pritchett (1998): reservoir behaviour during a 50-year production period and during a following recovery phase, indicated by the pressure and temperature development at a monitoring point placed between the production and reinjection wellfields (for details, see Pritchett (1998)). The change in the total steam volume in the reservoir is also depicted.

Pressure recovery proceeds the fastest, followed by temperature reestablishment. Table 2 shows that the relative recovery increases only slowly with time and that it takes several times longer than the production duration to reach a reasonable recovery (say 90 %). The recovery rate is strong in the beginning but decreases subsequently and theoretically only after infinite times can complete recovery be reached (“asymptotic behaviour”).

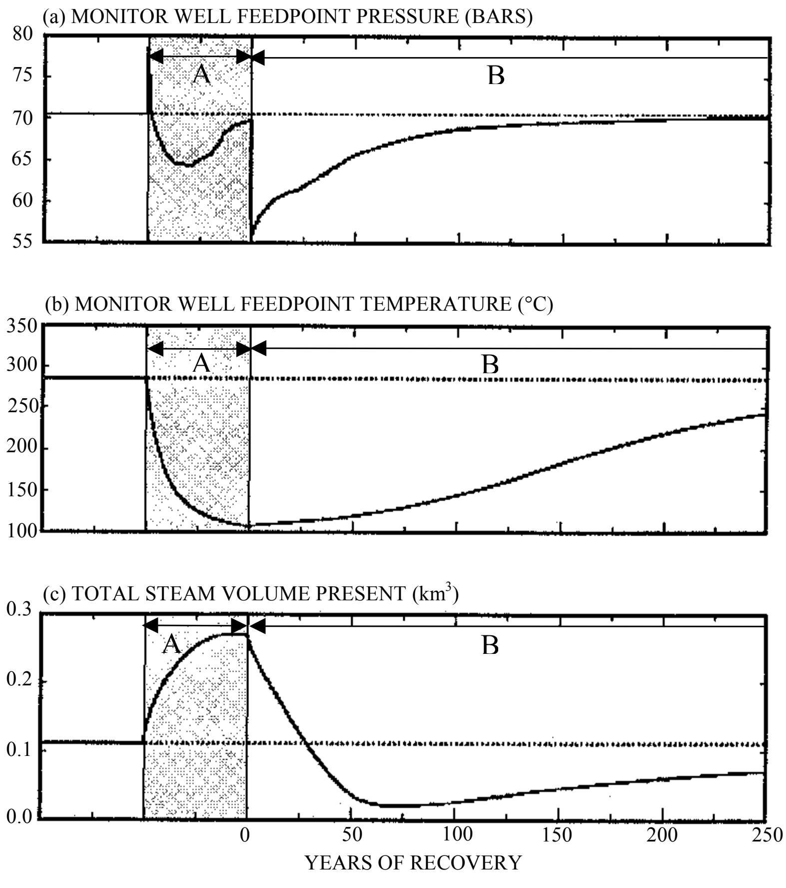

Figure 10: (a) Computed changes in monitor-well feedpoint pressure; (b) Feedpoint temperature; and (c) Total volume of steam present in reservoir; during 50-year production interval (A) and subsequent reservoir recovery (B). From Pritchett (1998).

Table 2: Relative recovery of a two-phase reservoir after 50 years production (data from Pritchett (1998).

Reservoir property	Years after production shut-down		
	50	100	250
Pressure	68 %	88 %	98 %
Temperature	9 %	21 %	77 %
Steam volume	-	5 %	55 %

6 Hot Dry Rock (HDR) / Enhanced Geothermal System (EGS)

Such a system attempts to extract heat by semi-open circulation from a fractured rock volume at considerable depth (several kilometers) between injection and production boreholes. The degree of fracturing is enhanced by technical means ("man-made fracturing").

The sustainability of HDR/EGS operation is a controversial subject: whereas Stefansson (2000) considers HDR as not renewable *("The hot dry rock method can not be classified as renewable energy source")*, Cataldi (2001) hails it by saying that *"Man-made fracturing is a way to enhance the level of sustainability."*

The thermal output of HDR/EGS depends on the efficiency of heat exchange in the fractured reservoir. The more heat exchange surface is encountered by the circulated fluid, the more efficient is the heat extraction. The output temperature (and that of the HDR/EGS reservoir) will decrease gradually; the decrease can be accelerated by effects like:

- Short circuiting - the circulated fluid follows preferential pathways instead of contacting extended heat exchange surfaces.
- Additional cooling of the rock mass if significant water losses in the system are replenished by adding cold water to the injection flow at the surface.

On the other hand, special effects like the creation of new heat exchange surfaces by cooling cracks might enhance the heat recovery. More field experience is needed to assess the efficiency and development in time of this effect.

In any case, the issues of HRD/EGS sustainability boils down to the question of thermal recovery of the rock mass after production stops. Usually, the lifetime of HDR/EGS systems is considered to be several decades. It can be expected that the recovery duration extends over time periods of similar magnitude, although the time-scale could be beyond economic interest. In favorable conditions like at the Soultz-sous-Fôrets (France), the site of the European Hot Dry Rock Project, hydraulic-convective heat and fluid resupply from the far field can be effective, thanks to large-scale permeable faults (Kohl et al., 2000). More detailed theoretical studies (by numerical simulation) are needed to establish a reliable base of HDR/EGS sustainability.

Further studies are also needed to determine, in a general sense, the residual heat which remains in a HDR/EGS reservoir when forced production rates are applied. Production at lower rates or by using production enhancement techniques enables the extraction of more heat and thus prolongs the economic life of a given reservoir. In particular, various operational strategies such as load following, variable well flow rates, innovative reservoir/power plant management e.g. by matching power plant design to reservoir production, should be considered.

7 Conclusions

Production of geothermal fluid and/or heat from a reservoir/resource decreases its fluid/heat content. After production stops, the recovery process driven by natural forces like pressure and temperature gradients, will start. The recovery shows asymptotic behaviour, being strong at the beginning and slowing down subsequently, the original state being re-established theoretically only after infinite time. However, practical replenishment (e.g. 95% recovery) will already be reached much earlier, generally on a time-scale of the same order as the lifetime of geothermal production systems (Rybach, 2002). In particular:

- For a high-enthalpy reservoir (utilised for electricity generation), sufficient recovery needs up to several hundred years, depending on local recharge conditions.
- For a doublet system (district heating), it takes 100 – 200 years.
- For shallow, decentral heat pump systems, the recovery time roughly equals the time of production (e.g. practical recovery in 30 years after a 30-year production period).
- The sustainability aspects of HDR/EGS systems still need to be addressed and investigated.

Thus geothermal resources can be considered renewable on time-scales of technological/societal systems, and do not need geological times as fossil fuel reserves do (coal, oil, gas). Recovery of high-enthalpy reservoirs is accomplished at the same site at which the fluid/heat is extracted. For the doublet and heat pump systems, truly sustainable production can be achieved.

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