# GEOTHERMAL SUSTAINABILITY

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## ABSTRACT

Geothermal energy is classified as a renewable resource, where "renewable" describes a characteristic of the resource: the energy removed from the resource is continuously replaced by more energy on time scales similar to those required for energy removal. Consequently, geothermal exploitation is not a "mining" process. Geothermal energy can be used in a "sustainable" manner, which means that the production system applied is able to sustain the production level over long periods of time. The longevity of production can be secured and sustainable production achieved by using moderate production rates, which take into account the local resource characteristics (field size, natural recharge rate, etc.).

The production of geothermal fluid/heat continuously 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 regeneration of geothermal resources is a process, which occurs over various time scales, depending on the type and size of the production system, the rate of extraction, and on the attributes of the resource. In general, production occurs over a certain length of time.

Time scales for re-establishing the pre-production state following the cessation of production have been examined using numerical model simulations for: 1) heat extraction by geothermal heat pumps; 2) the use of doublet system on a hydrothermal aquifer for space heating; 3) the generation of electricity on a high enthalpy, two-phase reservoir; and, 4) an enhanced geothermal system. The results show that after production stops, recovery driven by natural forces like pressure and temperature gradients begins. The recovery typically shows asymptotic behavior, being strong at the start, and then slowing down subsequently, and theoretically taking an infinite amount of time to reach its original state. However, practical replenishment (e.g. 95%) will occur much earlier, generally on time scales of the same order as the lifetime of the geothermal production systems.

## INTRODUCTION

Renewability and sustainability are terms often used and discussed. It is important to stress that the former concerns the nature of a resource and the latter applies to how a resource is utilized (Axelsson, et al., 2002). The relevance of these ideas to geothermal energy utilization is described below.

The ultimate source of geothermal energy is the immense heat stored within the earth: 99% of the earth's volume has temperatures >1000°C, with only 0.1% at temperatures <100°C. The total heat content of the earth is estimated to be about $10^{13}$ EJ and it would take over $10^9$ years to exhaust it through today's global terrestrial heat flow of 40 million MWt. The internal heat of the earth is mainly provided by the decay of naturally radioactive isotopes, at the rate of 860 EJ/yr – about twice the world's primary energy consumption (443 EJ in 2003). Thus, the geothermal resource base is sufficiently large and basically ubiquitous.

Without utilization, the terrestrial heat flow is lost to the atmosphere. In this case, the isotherms run parallel to the earth's surface (i.e. horizontal in flat terrain) and the perpendicular heat flow lines point towards it. If, instead, the isotherms are deformed and the heat flow lines diverted towards heat sinks, the heat flow can be captured (Figure 1). Production of heat/fluid from geothermal reservoirs leads to the formation of such heat sinks and/or hydraulic pressure depressions. Their effects will be treated in more detail below.

Heat/fluid (along with its heat content) can be produced from a geothermal resource at different extraction rates. Excessive production could bring economic benefits, like earlier return of investment, but could also lead to resource depletion or even deterioration. However, by using moderate production rates, which take into account the local resource characteristics (field size, natural recharge rate, etc.), the longevity of production can be secured and sustainable production achieved.

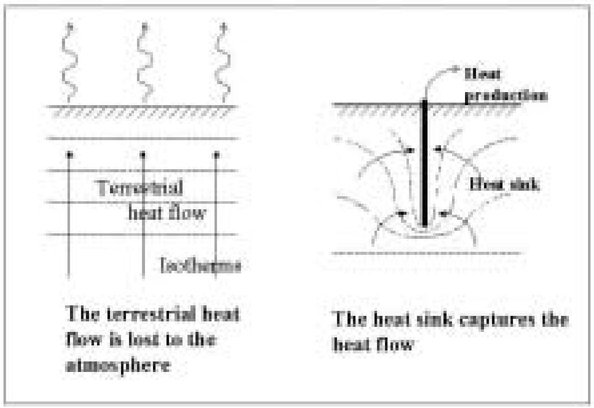

*Figure 1. Principle of geothermal heat extraction and production*

## "MINING" GEOTHERMAL RESOURCES?

Geothermal heat and/or fluid extraction is frequently described as "mining", however, this analogy is absolutely wrong. When a mineral deposit is mined and the ore removed, it will be gone forever. Not so for geothermal; being renewable, the replenishment of geothermal resources (heat and fluid) will always take place, albeit sometimes at slow rates. This incorrect analogy also leads to legal problems and obstacles, and in reality, geothermal energy cannot be defined in physical terms as a mineral resource.

The regeneration of geothermal resources is a process that occurs over various time scales, depending on the type and size of the production system, the rate of extraction, and the attributes of the resource.

After production stops, the resources recover by natural processes. The production of geothermal fluid/heat continuously creates a hydraulic/heat sink in the reservoir. This leads to pressure and temperature gradients, which in turn–both during production and after its cessation– generate fluid/heat inflows towards re-establishing the pre-production state (Rybach, et al., 2000). The question of regeneration boils down to the rate of fluid/heat re-supplies. The time scales for re-establishing pre-production states are examined below for four resource types and utilization schemes: 1) extraction of shallow heat 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; 4) enhanced geothermal systems (EGS). Numerical model simulations were used.

## GEOTHERMAL REGENERATION TIME SCALES

### *Geothermal Heat Pumps*

Geothermal heat pumps (GHP) are ground-coupled heat pumps; they operate with subsurface heat exchanger pipes (horizontal or vertical), or with groundwater boreholes (for an overview see Lund, et al., 2003).

The question of sustainability of GHPs in general, and of borehole heat exchanger (BHE)-coupled heat pumps boils down to: how long can such systems operate without a significant drawdown in production, i.e. becoming economically unviable. Therefore the long-term production behavior of BHE-based GHPs needs to be addressed.

After a period of operation, the BHE creates a cylindrically shaped heat sink in the ground with isotherms concentrated near the BHE (for details see Eugster and Rybach, 2000). The pronounced heat sink forms a cigar-shaped isotherm pattern, with the BHE as its center (Figure 2). The heat sink creates strong temperature gradients in the BHE vicinity, which in turn lead to heat inflow directed radially towards the BHE, to replenish the deficit created by the heat extraction. The heat flow density attains rather high values (up to several W/m$^2$), compared to the terrestrial heat flow (80 – 100 mW/m$^2$).

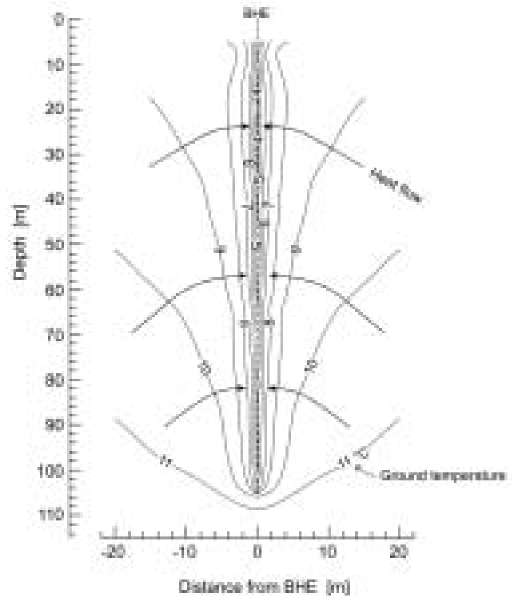

*Figure 2. Calculated temperature isolines around a 105 m deep BHE, during the coldest period of the heating season 1997 in Elgg, ZH, Switzerland. The radial heat flow in the BHE vicinity is around 3 W/m$^2$ (from Rybach and Eugster, 2002).*

During the production period of a BHE (operating in the heating-only mode), the drawdown of the temperature around the BHE is strong during the first few years of operation (Figure 3). Later, the yearly deficit decreases asymptotically. Fol-

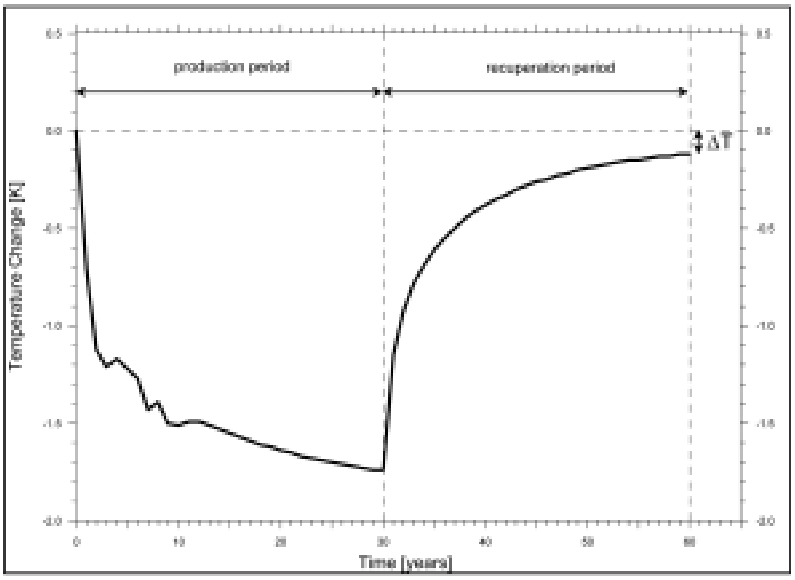

*Figure 3. Calculated ground temperature change at a depth of 50 m and at a distance of 1 m from a 105 m long BHE over a production period and a recuperation period of 30 years each (from Eugster and Rybach, 2000).*

lowing heat extraction shutdown, regeneration of the resource begins. During this recovery period (after an assumed 30 years of operation), the ground temperature shows a similar behavior: during the first years, the temperature increase is rapid, but then 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.

The results of numerical modelling for a single BHE shows that the long-term performance of the BHE/HP system stabilizes at a somewhat lower, but quasi-steady level, relative to initial conditions, after the first 10 years. Thus, sustainable operation can be achieved. The basic studies of long-term performance presented here apply to a single BHE. Similar studies of multiple BHE systems yielded comparable results (Signorelli, et al., 2005).

### *Doublet System Using a Hydrothermal Aquifer*

The heat content of a deep aquifer can be utilized 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), and the cooled water is reinjected into the aquifer by a second borehole at a sufficient distance from 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 at 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; and production at that rate can be sustained.

The town of Riehen, near Basel, hosts the first and only geothermal based district heating system in Switzerland, with a capacity of 15 MWt. The use of the doublet system started in 1994. In 1998, an extension of the district heating network into the neighbouring German town of Lörrach was established. For this system, it is essential to secure the production temperature without a considerable drawdown for about 30 years. Numerical simulations performed with the FE-code FRACTure (Kohl, 1992; for details about the modelling and the site see Mégel and Rybach, 2000) demonstrated that the geothermal circuit fulfills this condition.

The steady state production temperature is not reached even after 300 years. The development of the temperature can be characterized by considering the temperature change $\Delta T$ over a given time period, e.g. 10 years. This curve indicates the asymptotic behavior of the production temperature. The maximum value of -0.7°K/10 years is obtained after 20 years production, with the temperature drop decreasing to -0.15°K/10 years after 300 years production. Thus, practically constant heat production can be sustained.

Practical proof of sustainable doublet system operation is provided by the operational experience with the numerous doublet installations in the Paris Basin. Most of these systems have operated since the early 1970s and, so far, no production temperature or water level drawdowns have been observed (Ungemach and Antics, 2006).

### *High-Enthalpy Two-Phase Reservoir*

Resources of this type are widely used to generate electricity. Some of them show strong signs of pressure depletion. Although this can be beneficial to some reservoirs by locally stimulating increased hot fluid recharge, if a new pressure equilibrium is not established before the pressures drop too far, then well production rates become uneconomical.

Reinjection schemes are increasingly being introduced to help sustain pressures and overcome this problem. Reinjection, however, can cause temperature decreases in the resource volume. This problem, together with the high production rates dictated by economic constraints, rather than by balancing the natural re-supply, can limit the productive lifetime of power plants to a couple of decades.

A thorough theoretical study of the electrical production/recovery cycle of a hypothetical reservoir with operational characteristics typical of lower-permeability two-phase reservoirs was conducted by Pritchett (1998) using a maximum permeability (both horizontal and vertical) of 10 md and a relatively high production ratio [(produced energy)/(natural energy recharge)] estimated to be ~6.1 (O'Sullivan and Mannington, 2005). This ratio can vary widely depending on local resource characteristics. The study addressed the change in electricity generating capacity with time for 50 years of continuous two-phase fluid production; then examined the subsequent recovery after shutdown of the power plant operation.

The study shows that pressure recovery occurs much faster than temperature re-establishment. Table 1 shows that the relative recovery increases 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 complete recovery is reached theoretically only after an infinite time (asymptotic behavior).

### *Enhanced Geothermal System (EGS)*

Such a system attempts to extract heat by semi-open circulation through 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 thermal output of an EGS depends on the efficiency of heat exchange in the fractured reservoir. The more heat exchange surface that is encountered by the circulated fluid,

*Table 1. 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 % |

the more efficient is the heat extraction. The output temperature (and that of the EGS reservoir) will gradually decrease, though the decrease can be accelerated by effects such as short-circuiting, whereby the circulated fluid follows preferential pathways instead of contacting extended heat exchange surfaces, and 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 with time of this effect.

In any case, the issue of EGS sustainability boils down to the question of thermal recovery of the rock mass after production stops. The lifetime of EGS systems is usually 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. With favorable conditions like at Soultz-sous-Fôrets (France), hydraulic-convective heat and fluid re-supply from the far field can be effective, thanks to large-scale permeable faults (Kohl, et al., 2000). More detailed theoretical studies using numerical simulation are needed to establish a reliable base for EGS sustainability.

Further studies are also needed to determine, in a general sense, the residual heat, which remains in an EGS reservoir when excessive production rates are applied. Production at lower rates and/or 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 and innovative reservoir/power plant management (e.g. by matching power plant design to reservoir production) should be considered.

### *Regeneration Time-Scale Summary*

In summary, the following general comments about geothermal regeneration can be made. Production of geothermal fluid and/or heat from a reservoir/resource decreases its fluid/heat content, but also increases the natural recharge rate into created pressure and temperature sinks (i.e. dynamic recovery). A new and sustainable equilibrium condition can be established. The recovery process begins after production stops, driven by natural forces resulting from pressure and temperature gradients. The recovery typically shows asymptotic behavior, being strong at the beginning and slowing down subsequently, with the original state being re-established theoretically only after an infinite time. However, practical replenishment (e.g. 95% recovery) will be reached much earlier, generally on time-scales of the same order as the lifetime of the geothermal production systems.

## THE KEY ISSUE: THE SUSTAINABLE PRODUCTION LEVEL

When producing from a geothermal resource the sustainability will depend on the initial heat and fluid content and their regeneration rates (Wright, 1995). In addition, the reaction of the resource to production will largely depend on the rate of heat/fluid extraction. With high extraction rates the energy yield will be correspondingly high at the beginning (and with it the economic reward) but the energy delivery will decrease significantly with time, and can cause the breakdown of a commercially viable operation.

Lower production rates can secure the longevity of production, i.e. relatively constant production rates can be sustained. In addition, sustainable production rates can provide similar total energy yields to those achieved with high extraction rates. To demonstrate this, the results of a study comparing high and low level production from an EGS model are summarized (for details see Sanyal and Butler, 2005). The model reservoir had an area of 3.66 km x 3.66 km, with a vertical extension between 1.22 km and 2.74 km depth. The average initial reservoir temperature was 210°C. A three-dimensional, double-porosity, finite-difference numerical scheme was used to calculate power generation from this hypothetical EGS reservoir. A five-spot borehole array (injector at the model center and production well at each corner of a square) with high 1800 t/hr (500 l/s) and low 454 t/hr (126 l/s) production rates was considered (injection flow rate = production flow rate).

Production at the high rate yielded higher power generation capacity at the beginning (45 MWe). A parasitic load of nearly 10 MWe was needed to pump the high fluid circulation rate through the system. The fluid production temperature decreased with time and reservoir depletion resulted in production stopping after 20 years (Figure 4). The total energy produced amounted to 245 MWe-year. At the lower circulation rate, the starting capacity was only 12 MWe (Figure 5), but the pumping load was nearly negligible. The temperature decline was also much less and the power generation capacity prevailed well beyond 30 years. The total energy produced over 30 years, 250 MWe- year, was very similar to that from the excessive production.

This example demonstrates that with lower extraction rates, longevity of the resource, and thus sustainable production, can be achieved and still generate as much energy as from excessive production. The level of sustainable production depends on the utilization technology as well as on the local geological conditions and resource characteristics. Its determination needs specific studies, especially model simulations of long-term production strategies.

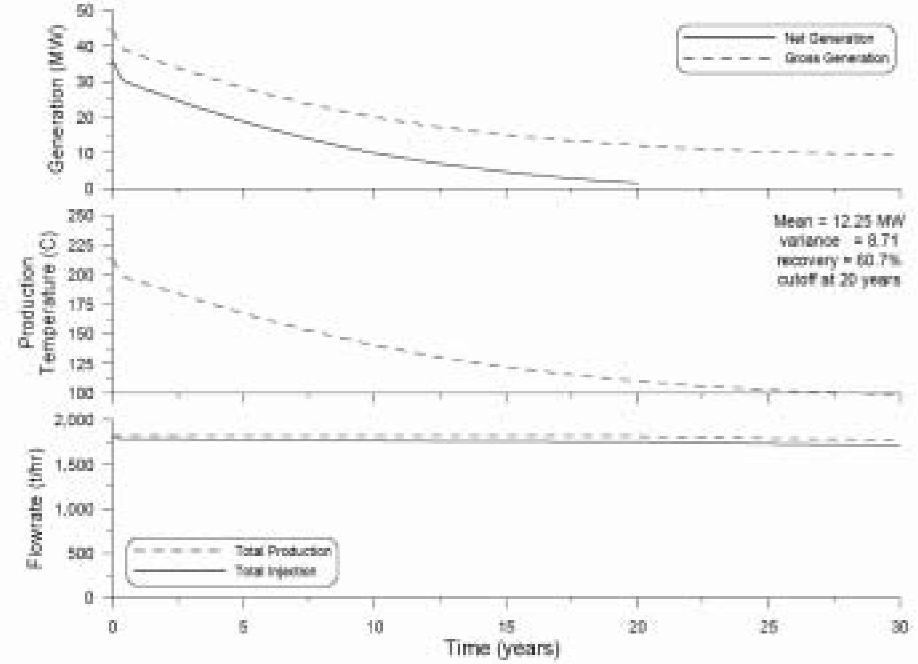

*Figure 4. Power generation from an EGS system with high circulation rate (500 l/s) starts with 45 MWe capacity but terminates after 20 years with a total generation of 245 MWe -years (from Sanyal and Butler 2005).*

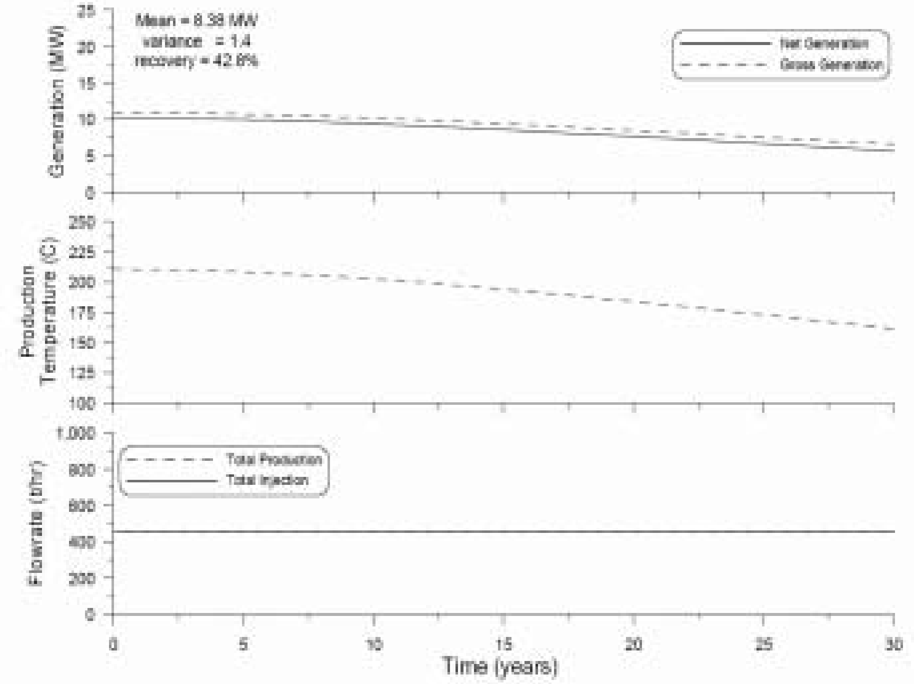

*Figure 5. Lower circulation rate (126 l/s) yields long-lasting power production with total generation of 250 MWe-years (from Sanyal and Butler, 2005).*

## CONCLUSIONS

Any "balanced" fluid/heat production by a geothermal utilization scheme, i.e. which does not produce more than the natural recharge re-supplies, can be considered "fully" sustainable. A natural thermal spring, issuing since Roman times, is an impressive example.

Production of geothermal fluid and/or heat from a reservoir/resource decreases its fluid/heat content, but also increases the natural recharge rate into created pressure and temperature sinks (i.e. dynamic recovery). A new and sustainable equilibrium condition can be established.

Production rates that exceed the long-term rate of recharge will eventually lead to reservoir depletion, which could stop economic production.

The continuous production of geothermal fluid and/or heat creates a hydraulic/heat sink in the reservoir. This leads to pressure and temperature gradients, which in turn– both during and after termination of production– generate fluid/heat inflow towards re-establishing the pre-production state.

Unlike for mining (e.g. mining out an ore body), there will be geothermal resource regeneration. The recovery typically shows asymptotic behavior, 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 be reached relatively early, generally on a time-scale of the same order as the lifetime of geothermal production systems.

Recovery of high-enthalpy reservoirs is accomplished at the same site at which the fluid/heat is extracted. In addition, for the doublet and heat pump systems, truly sustainable production can be achieved. 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).

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.

Long-term production from geothermal resources should be limited to sustainable levels, although short periods of extra production may be an appropriate means of rapidly establishing pressure and temperature sinks, and thereby encouraging greater flows of hot recharge from much larger underlying or peripheral resources.

The level of sustainable production depends on the utilization technology as well as on the local geothermal resource characteristics. Its determination needs specific studies, especially model simulations of long-term production strategies, for which exploration, monitoring and production data are required.

Further sustainability research is needed in several areas.

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## REFERENCES

Axelsson, G., V. Stefansson,, and Y. Xu, 2002. "Sustainable Management of Geothermal Resources." In: Liu Jiurong (ed.), *Proceedings* 2002 Beijing International Geothermal Symposium, Beijing, China, 29-31 October 2002, pp. 277-283.

Eugster, W.J. and L. Rybach, 2000. "Sustainable Production from Borehole Heat Exchanger Systems." *Proceedings* World Geothermal Congress 2000, Kyoshu – Tohoku, Japan, pp. 825-830.

Kohl, T., 1992, Modellsimulation Gekoppelter Vorgänge beim Wärmeentzug aus Heissem Tiefengestein." Ph.D. Thesis ETH Zurich, no. 9802.

Kohl, T., D. Bächler, and L. Rybach, 2000. "Steps Towards a Comprehensive Thermo-Hydraulic Analysis of the HDR Test Site Soultz-sous-Forêts." *Proceedings* World Geothermal Congress 2000, Kyushu-Tohoku, Japan, pp. 2671-2676.

Lund , J.W., B. Sanner, L. Rybach, R. Curtis, and G. Hellström, 2003. "Ground Source Heat Pumps – A World Review." *Renewable Energy World*, July-August 2003, pp. 218-227.

Mégel, T, and L. Rybach, 2000. "Production Capacity and Sustainability of Geothermal Doublets." *Proceedings* World Geothermal Congress 2000, Kyoshu – Tohoku, Japan, pp. 849-854.

O'Sullivan, M. and W. Mannington, 2005. "Renewability of the Wairakei-Tauhara Geothermal Resource." *Proceedings* World Geothermal Congress 2005 (CD-ROM, paper 0508), 8 p.

Pritchett, J.W., 1998. "Modelling Post-Abandonment Electrical Capacity Recovery for a Two-Phase Geothermal Reservoir." Geothermal Resources Council *Transactions*, v. 22, pp. 521-528.

Rybach, L., and W.J. Eugster, 2002. "Sustainability Aspects of Geothermal Heat Pumps." *Proceedings* 27th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, pp. 50-64.

Rybach, L., T. Mégel, and W.J. Eugster, 2000. "At What Time-Scale are Geothermal Resources Renewable?" *Proceedings* World Geothermal Congress 2000, Kyoshu – Tohoku, Japan,, v. 2, pp. 867-873.

Rybach, L., and M. Mongillo, 2006: Geothermal Sustainability – A Review with Identified Research Needs. Geothermal Resources Council *Transactions* v. 30, pp. 1083-1090

Sanyal, S.K., and S.J. Butler, 2005. "An Analysis of Power Generation Prospects from Enhanced Geothermal Systems." *Proceedings* World Geothermal Congress 2005, Antalya, Turkey (CD-ROM, paper 1632, 6 p.).

Signorelli, S., T. Kohl, and L. Rybach, 2005. "Sustainability of Production from Borehole Heat Exchanger Fields." *Proceedings* World Geothermal Congress 2005, Antalya, Turkey (CD-ROM, paper 1450, 6 p.).

Ungemach, P., and M. Antics, 2006. "Geothermal Reservoir Management – a Thirty Year Practice in the Paris Basin." ENGINE Lauching Conference, Orléans, France. http://conferences-engine.brgm.fr/conferenceDisplay.py?confId=0

Wright, P.M., 1995. "The Sustainability of Production from Geothermal Resources." *Proceedings* World Geothermal Congress 1995, Florence, Italy, pp. 2825-2836.