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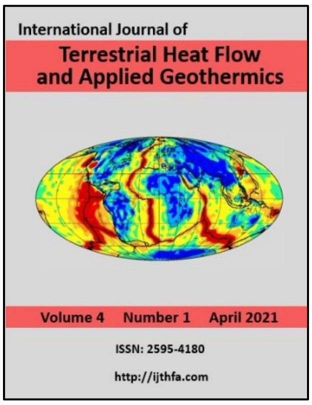

Geothermal Sustainability or Heat Mining?

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Abstract

"Heat mining" is, in fact a complete deceptive misnomer. When a mineral deposit (e.g. copper) is mined and the ore has been taken out, it will be gone forever. Not so with geothermal resources: The heat and the fluid are coming back! Namely, the heat and fluid extraction create heat sinks and hydraulic minima; around these, strong temperature and pressure gradients develop. Along the gradients, natural inflow of heat and fluid arises to replenish the deficits. The inflow from the surroundings can be strong: around borehole heat exchangers, heat flow densities of several W/m^2 result, whereas terrestrial heat flow amounts only to about 50 – 100 mW/m^2. The regeneration of geothermal resources after production, in other words, extraction of fluid and/or heat is a process that runs over different timescales, depending on the kind and size of the utilization system, the production rate, and the resource characteristics. The resource renewal depends directly on the heat/fluid backflow rate. Heat and fluid production from geothermal resources can be accomplished with different withdrawal rates. Although forced production is more attractive financially (with quick payback), it can nevertheless degrade the resource permanently. The longevity of the resource (and thus the sustainability of production) can be ensured by moderate production rates. The sustainable geothermal production level depends on the utilization technology as well as on the local geologic conditions. The stipulation of the sustainable production level requires specific clarifications, especially by numerical modelling, based on long-term production strategies. In general, resource regeneration proceeds asymptotically: strong at the beginning and slowing down subsequently, reaching the original conditions only after infinite time. However, regeneration to 95 % can be achieved much earlier, e.g. within the lifetime of the extraction/production system. In other words, geothermal resources can regrow – like biomass. Concerning the requirements for sustainable production, four resource types and utilization schemes are treated, by numerical model simulations.: 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; 4) Enhanced Geothermal Systems (EGS).

1. Introduction

Renewability and sustainability are terms often used and discussed nowadays. In the following, the relevance of these notions for geothermal energy utilization is discussed and the view of the International Energy Agency (IEA) GIA is outlined (the cooperative geothermal R&D activities of the IEA are assembled within the Geothermal Implementing Agreement GIA).

The ultimate basis of geothermal energy is the immense heat stored in the earth's interior. Note that 99% of the earth globe is at temperatures >1000°C, only 0.1% has temperatures <100°C. The global heat loss of the earth amounts to 40 million MW. The total heat content of the earth 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 (Dickson and Fanelli, 1995, p.3). 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, which is mainly supplied by the decay heat of natural radioisotopes (Rybach et al., 2000). Thus, the resource base is sufficiently large and is basically ubiquitous.

Without harvesting the terrestrial heat flow is given off to the atmosphere. Instead, it can be captured, and the heat flow lines can be diverted towards heat sinks (Figure 1).

In case of no geothermal resource utilization the isotherms run parallel to the surface (i.e. horizontal in flat terrain), with heat extraction the isotherms are deformed. The heat flow lines run always perpendicular to the isotherms. Production of heat and/or fluid from geothermal resources leads to the formation of heat sinks and/or hydraulic pressure depressions. Their effects will be treated in more detail further below.

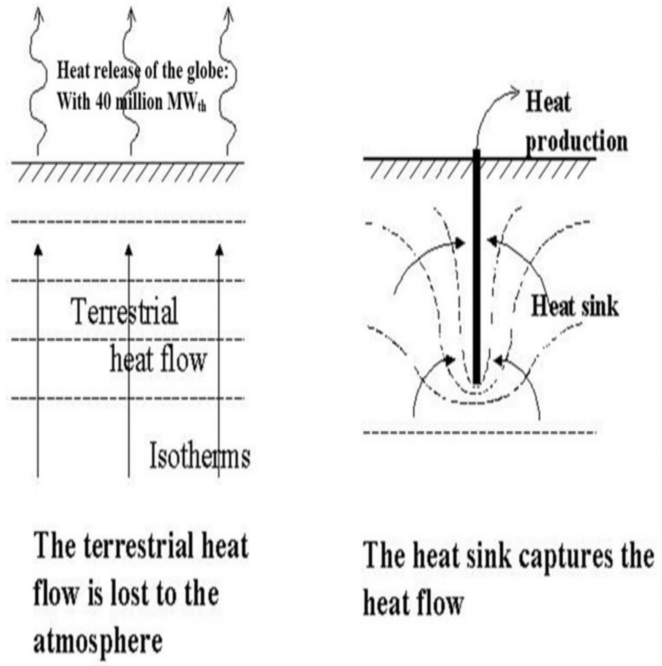

Figure 1 - Schematic illustration of the principle of geothermal heat extraction and production.
Arrows indicate direction of heat flow. The left panel refers to a scheme where without heat extraction, terrestrial heat escapes to the atmosphere. The right panel refers to a scheme where heat inflow replenishes the heat sink, created by the heat extraction.

Production of heat and/or fluid (along with its heat content) from a geothermal resource can be realized by different extraction rates. Forced production could bring about economic benefits like earlier return of investment but could lead to resource depletion or even deterioration. By applying moderate production rates, taking into account the local conditions (field size, natural recharge rate etc.), the longevity of production can be secured and thus production sustainability can be achieved.

2. Renewability and sustainability

In general, geothermal energy is labelled 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 etc. This attribute applies only with certain restrictions, which must be addressed in a fully objective manner.

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 (Axelsson et al., 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 resource will be described.

3. 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 utilization 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.

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 utilization 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.

Geothermal resources are often taken into forced production (of the reservoir fluid as the heat carrier), mainly to meet economic goals like a quick payback of investments for exploration and equipment, in such a way that reservoir depletion is the result. There are numerous examples for this approach worldwide, the most prominent is the vapor-dominated field of The Geysers, California/USA. Figure 2 shows the change of production with time, and the effect of reinjection (of wastewater piped over a distance of about 50 kilometers from Clear Lake/CA, starting in January 1998).

Reinjection could halt the production decline and more or less stabilize production.

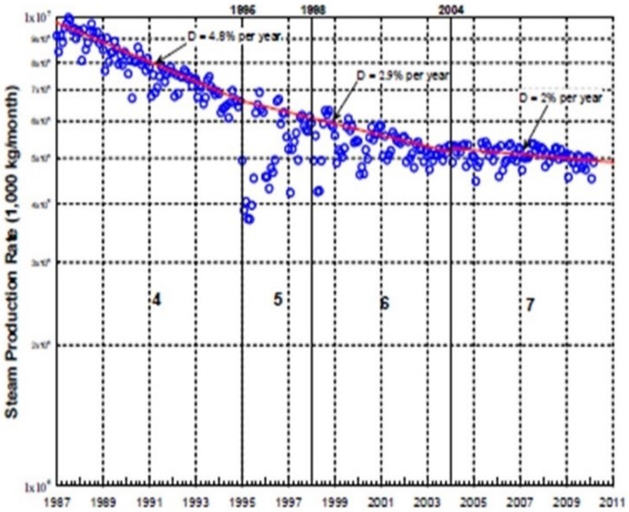

Figure 2 - Production decline and reinjection effect at The Geysers (total steam production rate). Reinjection started January 1989. From Sanyal and Enedy (2011).

4. “Mining” of geothermal resources? No!

In many brochures, publications, presentations etc. geothermal heat and/or fluid extraction is described as “mining”. It must be strongly emphasized that this analogy is absolutely wrong. Where and when a mineral deposit is mined and the ore has been taken out, it will be gone there forever.

Not so in geothermal: the replenishment of geothermal resources (heat and fluid) will always take place, albeit at sometimes low rates. These will be addressed below. The wrong analogy leads also to legal problems and obstacles: in many countries, geothermal is often regulated by the mining law and permits are issued by mining authorities. In reality, geothermal energy cannot be defined in physical terms as a mineral resource; the mining offices in general are not specially trained to deal with geothermal problems.

The regeneration of geothermal resources is a process, which operates at various time scales, depending on the type and size of the production system, the rate of extraction, and on local conditions. In general, the production goes on over a certain length of time.

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. In other terms, geothermal resources regrow, like biomass.

The question of regeneration boils down to the rate of fluid/heat resupply. Concerning the time scales of re-establishing the pre-production state, four resource types and utilization schemes will be treated below: 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; 4) Enhanced Geothermal Systems (EGS). The renewal (connected with replenishment, regeneration) has been treated by numerical model simulations.

5. 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 borehole heat exchangers (BHE)-coupled GHP systems is different. During heat extraction operation, the BHE 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 by which a reliable operation can be secured also on the long term (i.e. sustainable operation) need to be established. 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.

The question of sustainability of GHPs in general, and of BHE coupled HPs boils down to the question: for how long such systems can 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.

In the following, the results of numerous investigations, based on field measurements and numerical modeling are summarized. The data and results originate from a commercially operated BHE installation (heating alone, one 100m long BHE) in Elgg near Zurich, Switzerland. Detailed descriptions and numerous details can be found in Rybach and Eugster (2010).

5.1. Short-and long-term ground recovery

The heat extraction by an operating BHE creates a heat sink in the ground, which has cigar-shape. The isotherms are, after a certain operational time, concentrated near the BHE. For details see Eugster and Rybach (2000). The pronounced heat sink forms an isotherm pattern, with the BHE as its center (see Figure 3). The heat sink creates steep temperature gradients in the vicinity of BHE, which in turn leads to heat inflow, directed radially towards the BHE, to replenish the deficit created by the heat extraction. Compared to average terrestrial heat flow (80 mW/m^2), the heat flow towards the BHE attains high values (up to several W/m^2 – see Figure 3).

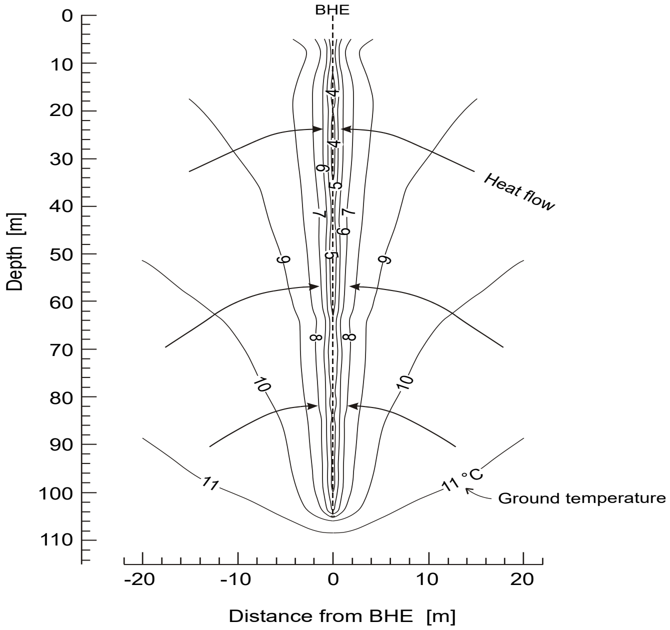

Figure 3 - Calculated temperature isolines around a 105 m deep BHE, during the coldest period of the heating season of 1997 in Elgg/ZH, Switzerland. The radial heat flow in the vicinity of BHE is assumed to be 3 W/m^2 (Adapted from Rybach and Eugster, 2002).

The cigar-shape of the pattern with dense isolines has been further confirmed by field measurements in observation boreholes (for details see Rybach and Sanner, 2000).

After cessation of heat extraction, recovery of the ground temperature begins. During the production period, the drawdown of the isotherms around the BHE is high during the first few years of operation (see Figure 4). Later, the yearly temperature deficit asymptotes to very small values. During the recovery period after stopping BHE operation (assumed to happen after 30 years of operation), the ground temperature shows a similar behavior: during the first years, the modelled temperature recovery is rapid, but tends with increasing recovery time asymptotically towards zero (details in Rybach et al., 1992, Rybach and Eugster, 2002). The time to reach nearly complete recovery depends on how long the BHE has been in operation. Principally, the recovery duration corresponds to the operation period.

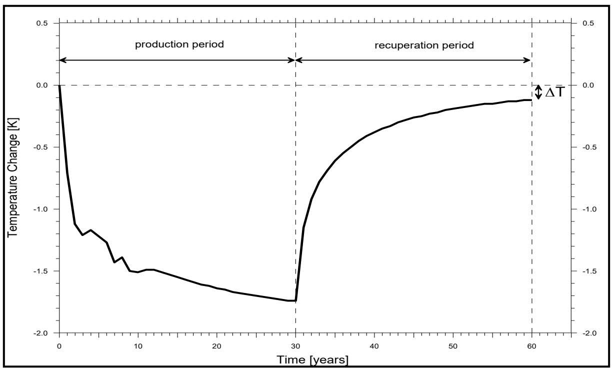

Figure 4 - Calculated ground temperature change at a depth of 50m and at a distance of 1m from a 105 m long BHE during a production period and a recovery period of 30 years each (Rybach and Eugster, 2010). After 30 years of recovery the deficit (ΔT).

5.2. Long-term operational experience

Numerous GHP installations have operated fully satisfactorily in Switzerland, for decades. A systematic evaluation of operating experience was first performed in 1985 (Rohner, 1994), addressing GHP systems with BHEs, running for 9–14 years at that time. The study reported consistently positive experience. A new project, financed by the Swiss Federal Office of energy, systematically evaluated the operational experience of 33 GHP systems in Switzerland, functioning over 25–31 years. The investigation results, presented in Signorelli et al. (2010), confirmed the findings of the first study

The data acquisition system at Elgg was switched on again in fall of 2001. Data gathering started on 27 August and ended on 25 September. One temperature sensor did not function; the missing data have been estimated by extrapolation (for more details see Eugster, 2001). The measurements are shown in Figure 5; it is evident that the ground temperatures stabilized in the last couple of years of system operation.

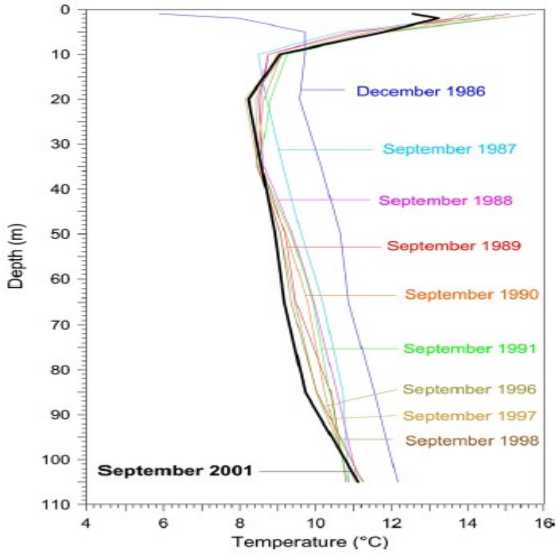

Figure 5 - Ground temperature profiles at 0.5 m distance from a 105 m deep operating BHE at Elgg/ZH, repeatedly measured over 15 years. The last measurement is from fall 2001 (curve "September 2001") (Eugster, 2001).

In particular, Figure 5 shows temperature profiles measured in the vicinity of the BHE at the beginning of subsequent heating seasons. The ground temperatures decrease from year to year, but less and less. During summer they recover. Thus, sustainable production has been achieved over the 15 years of system operation. The observational borehole with temperature sensors at 1m distance from the BHE shows practically identical results (Eugster, 2001).

Nowadays, GHP installations with numerous are common worldwide. Sustainable production from multiple BHEs is described in Signorelly et al., 2005).

5.3. Heating and cooling with GHPs

The subsurface can be utilized as a heat sink as well as a heat store, utilizing the immense renewable storage capacity of the ground. In moderate climate the ground below about 15 m depth is in summer significantly colder than outside air. Thus, a large geothermal store volume with favorable heat capacity is available where the heat can be exchanged (extracted from the building and deposited in summer, extracted from the ground store and supplied to the building in winter). By these means, the ground provides a "built-in" sustainability.

The thermal capacity of the system depends –besides on the volume– on the thermal and hydrogeologic characteristics of the installation site; these must be carefully considered in system dimensioning. In summer, most of the time the heat pump can be bypassed, and the heat carrier fluid circulated through the ground by the BHEs and through the heating/cooling distribution (e.g. floor panels). By these means the heat is collected from the building and deposited it in the ground for extraction in the next winter ("free cooling"). When free cooling alone cannot satisfy the cooling needs, heat pumps can be reversed for cooling since they can operate in normal (heating) and reverse (cooling) mode. This GHP utilization mode provides fully sustainable operation on the long term.

Here one example: At Untersiggenthal, Switzerland a GHP system operates with two 70 m deep BHEs. The total heating capacity for the single-family house is 11 kW thermal. Since the summer of 1996 the system is also being used for space cooling. Details about the system are given in Rybach and Eugster (2010). Figure 6 shows the return temperature of the fluid circulating in the BHEs over the years 1997–2008. Stability and sustainability are evident, thus sustainable operation characterizes this installation too.

Sustainability aspects of GHP systems have been addressed above, with emphasis on Borehole Heat Exchanger (BHE)/heat pump (HP) systems. BHE/HP are a feasible way to tap shallow geothermal resources which, located directly below our feet, represent a unique, ubiquitous and therefore enormous geothermal potential, which can be utilized in a sustainable manner. Detailed descriptions about design, installation and operation of GHP systems are given in Lund et al. (2003) or Rybach (2012).

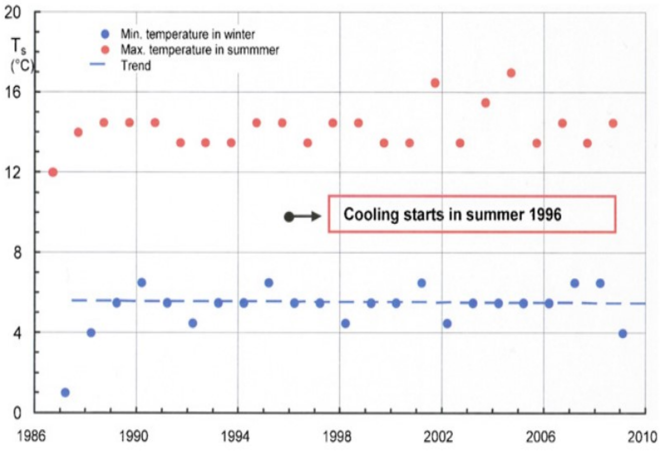

Figure 6 - Stability of temperature from borehole heat exchangers during the period 1987–2008. Ts: return fluid temperature from BHE (upper dots: in summer, lower dots: in winter). Data for a single-family house installation at Untersiggenthal, Switzerland. From Rybach and Eugster (2010).

6. 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), 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, the only geothermal based district heating system in Switzerland, with a capacity of 15 MW thermal, which supplies about 160 users. About 50% of the needed energy is covered by a geothermal doublet operation (production well 1547 m, reinjection well 1247 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 neighboring German town of Lörrach has been established. For details see Link et al. (2015).

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).

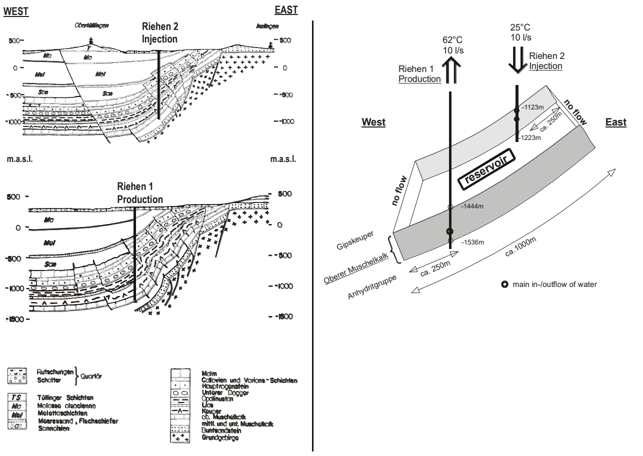

Figure 7 - Geological cross-section and conceptual model of the aquifer of the doublet operation in Riehen. From Mégel and Rybach (2000).

Additional attention is focused 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 characterized by considering the temperature change ΔT 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; 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.

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 the higher the shorter the cycle period is (Figure 9).

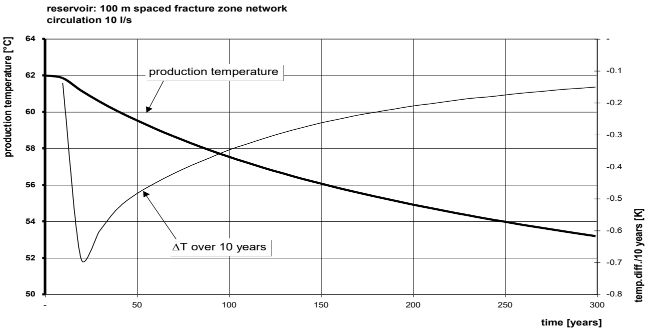

Figure 8 - Development of the production temperature for a 100 m spaced fracture zone reservoir model. From Mégel and Rybach (2000).

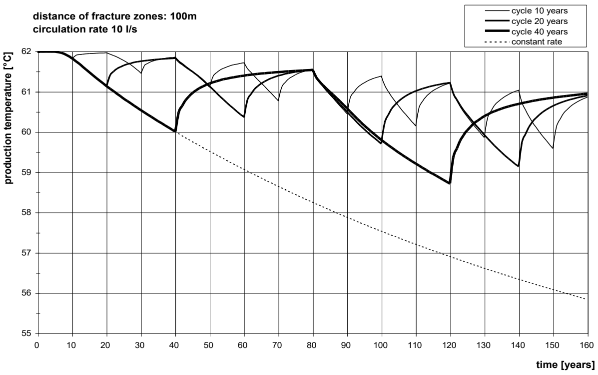

Figure 9 - Production temperature for production-recovery cycles of different duration in a doublet operation. From Mégel and Rybach (2000).

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.

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

Circulation scheme	Circulation rate [l/s]	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

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

The above approach and the achieved results are fully confirmed by a study of Satman (2011), as demonstrated by Figure 10. In particular, Satman (2011) states that "A comparison of the average reservoir temperature of production-recovery cycles of 18, 36, and 72 years shows that the temperature remains on a higher level for the shorter cycle periods, indicating that short production-recovery cycles produce more energy. The same conclusion was also reached by Megel and Rybach (2000). This is an important conclusion for geothermal projects with doublet and multi-doublet patterns."

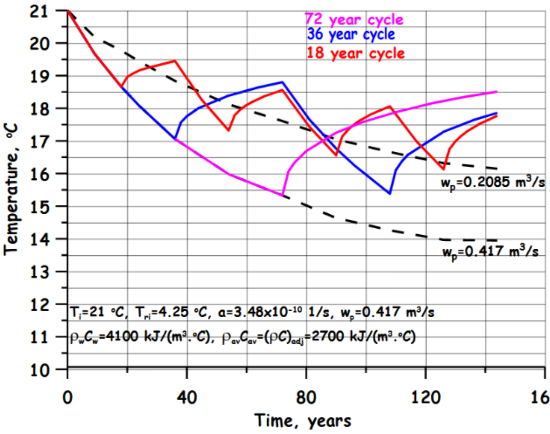

Figure 10 - Average reservoir temperature for production-recovery cycles of different duration in a doublet operation. From Satman (2011).

7. 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 reservoir volume; together with the production rates dictated by economic constraints rather than 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 11 shows the results of Pritchett (1998): reservoir behavior 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.

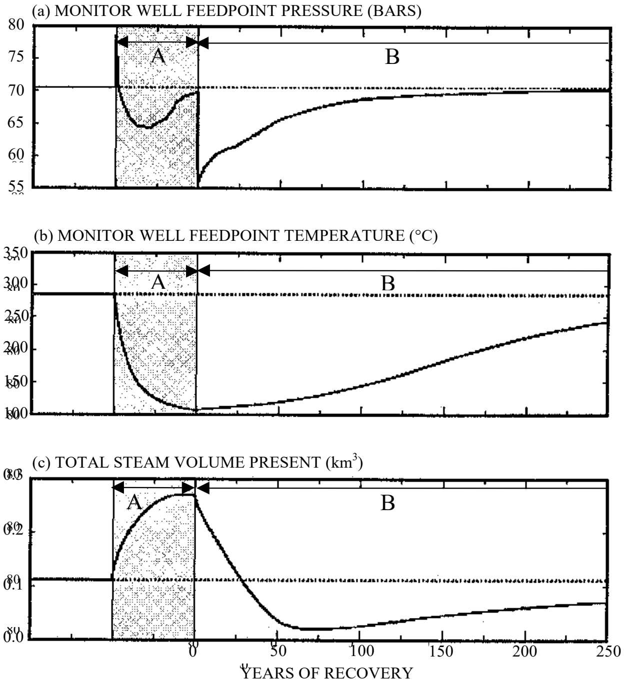

Figure 11 - Computed changes in monitor-well feed point pressure (a); feed point temperature (b); and total volume of steam present in reservoir (c), during 50-year production interval (A) and subsequent reservoir recovery (B). Horizontal lines: Asymptotes of recovery. From Pritchett (1998).

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 behavior").

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 %

8. 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 cannot 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. Figure 12 clearly shows this dependence in terms of the density of heat exchanging fracture surfaces; at the same time, it shows the heat extraction / heat recovery behavior. It also demonstrates that reservoir depletion and recovery behavior is the same for shallow and deep systems: it is asymptotic; strong at the beginning and slowing down subsequently.

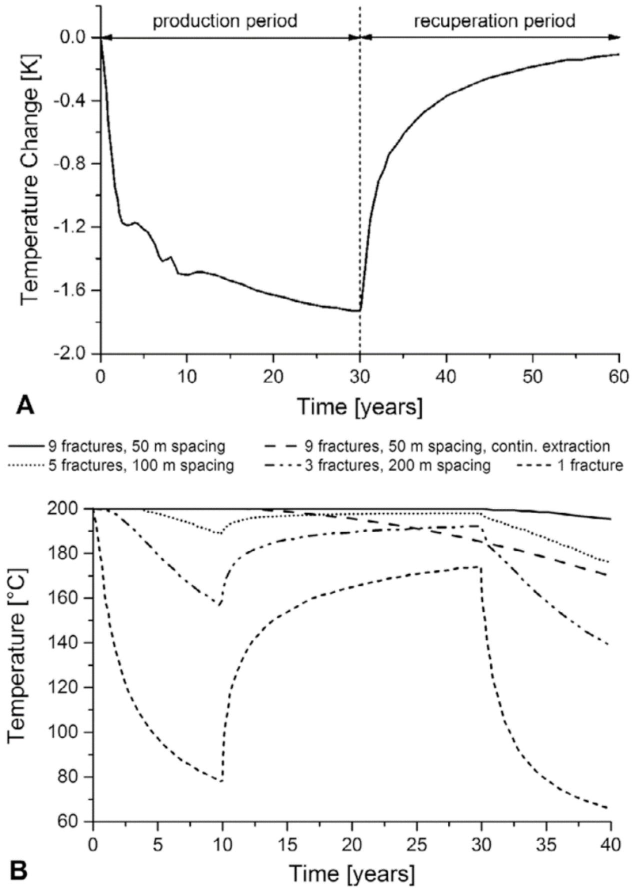

Figure 12 - Integrated depletion and recovery curves for shallow and deep production systems. A: ground temperature changes at 50 m depth and 1m distance from a producing 100 m long borehole heat exchanger – for the first 10 years measured, and the rest modelled (Rybach and Eugster, 2010). B: EGS fluid production temperatures with various heat exchanger fracture configurations (Fox et al. 2013). Heat transfer by conduction in both cases. The similarity of the curve shapes is conspicuous. Figure from Rybach and Kohl (2018).

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 timescale 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 an 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.

8.1. The key issue: The sustainable production level

When producing from a geothermal reservoir the sustainability will depend on the initial heat and fluid content and their regeneration (Wright, 1995). Besides, the reaction of the reservoir 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 significantly decrease with time and can cause the breakdown of a commercially feasible operation. The total energy yield during the operational period will amount to a certain number; for power generation this will be the total produced GWh_e.

Lower production rates can secure the longevity of production, i.e. a relatively constant production rate can be sustained. It will be shown below that with the moderate production rate to provide resource sustainability similar total energy yields can be achieved.

To demonstrate this, the results of a specific study for EGS (Sanyal and Butler 2005) will be summarized. In particular, a high and a low-level production from an EGS model are compared. The model reservoir domain has a volume 3.66 x 3.66 km with a vertical extension between 1.22 and 2.74 km depth. The average initial reservoir temperature was set at 210°C. Further details can be found in Sanyal and Butler (2005). The authors applied a three-dimensional, double-porosity, finite-difference numerical scheme to calculate power generation from this hypothetical EGS reservoir. For a five-spot borehole array (an injector at the model center and a production well at each corner of a square) two fluid circulation rates, a high (1800 tonnes/hr) and a lower (475 tonnes/hr) rate, have been considered (injection flow rate = production flow rate).

Production at the high rate yields higher gross power generation capacity at the beginning: 45 Megawatt Electrical (MW_e). A parasitic load of nearly 10 MW_e is needed to pump the high fluid circulation rate through the system. The fluid production temperature decreases with time and the reservoir depletion result in production stop after 20 years, see Figure 13). The total energy produced amounts to 245 MW year.

With the lower circulation rate, the starting capacity is only 12 MW_e (see Figure 14) but the pumping load is negligible. The temperature decline is also much less; the power generation capacity prevails well beyond 30 years. The total energy produced over 30 years, 250 MW_eyr, compares well with that of the forced production.

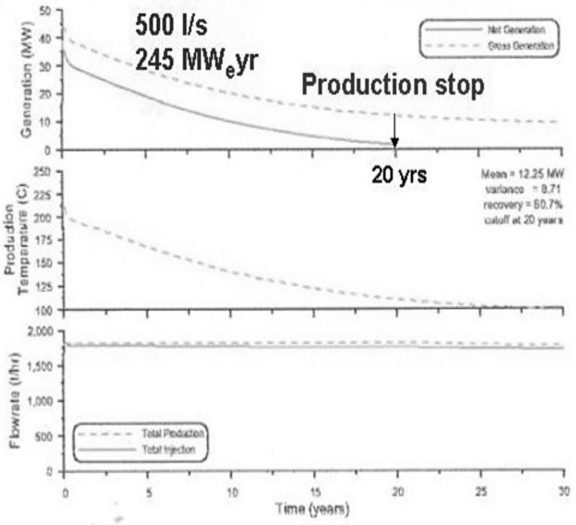

Figure 13 - Power generation from an EGS system with high circulation rate (from Sanyal and Butler 2005) starts with 55 MWe capacity but terminates after 20 years.

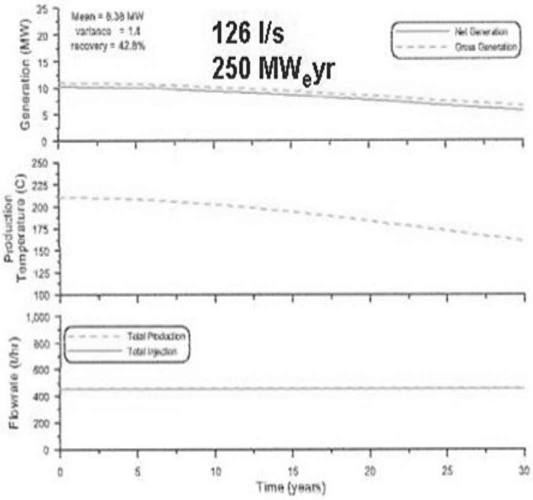

Figure 14 - Lower circulation rate yields long-lasting power production.

The results above demonstrate that with lower extraction rates the longevity of the resource and thus sustainable production can be achieved. The level of sustainable production depends on the utilization technology as well as on the local geological conditions. Its determination needs specific studies, especially model simulations of long-term production strategies.

9. Sustainability research needs

Even in view of numerous basic studies on geothermal production sustainability (Axelsson et al., 2001, 2002, 2004; 2010, 2020; Rybach et al., 1999, 2000, 2002, 2003; 2007; Sanyal 2005; Stefansson, 2000; Stefansson and Axelsson, 2003, 2004; Ungemach et al., 2005, 2006; Wright, 1995) there is a clear need for more sustainability research. Specific, focused investigations are needed in several areas:

- Compilation and analysis of successful examples for stabilizing reservoir performance during production (Larderello/Italy, Cappetti, 2004; Kawerau/New Zealand, Bromley, 2006a; Wairakei/New Zealand, Bromley, 2006b).
- Synoptic treatment of numerically modelled production technologies (steam-turbined power plant, geothermal doublet, ground-source heat pump) by a unified approach looking at the regeneration timescales.
- Numerical modelling of EGS considering long-term production/recovery, by different production scenarios like combined heat and power (CHP) production, load-following operation.
- Deriving "dynamic" recovery factors: these have to account for enhanced regeneration, driven by the strong hydraulic and thermal gradients created by fluid/heat extraction. (so far only "natural" conductive and convective recharge was considered; see e.g. Sanyal and Butler, 2004 and Sanyal, 2005).

10. Conclusions

- Geothermal heat mining is an inappropriate term: In conventional mining, the mined-out ore is gone and will never return, whereas geothermal resources regrow like biomass.
- Any "balanced" fluid/heat production by a geothermal utilization scheme, i.e. which does not produce more than the natural recharge resupplies, can be considered as fully renewable. A natural thermal spring, issuing since Roman times, is an impressive example.
- Production of geothermal fluid and/or heat from a reservoir decreases its fluid/heat content. Production rates that exceed the rate of recharge will lead with time to reservoir depletion, which could stop economic production.
- 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.
- Unlike with mining, there will be resource regeneration. The recovery 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 already be reached much earlier, generally on a timescale 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. Besides, for the doublet and heat pump systems, truly sustainable production can be achieved. Thus, geothermal resources can be considered renewable on timescales of technological/societal systems (30 – 300 years), 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.
- The level of sustainable production depends on the utilization technology as well as on the local geological conditions. Its determination needs specific studies, especially model simulations of long-term production strategies.
- Whenever possible, production from geothermal resources should be restricted to sustainable levels.

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