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Geothermal Sustainability—A Review with Identified Research Needs

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ABSTRACT

The immense store of heat in the earth (~10^{13} EJ), provided mainly by decay of natural radioisotopes, is the ultimate source for geothermal resources. It results in a global terrestrial heat flow of 40 million MW_t, which alone would take over 10^9 years to exhaust the earth's heat. So, the geothermal resource base is extremely large and ubiquitous.

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 and those typical of technological/societal systems*. 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 times*. However, excessive production is often pursued, mainly for economic reasons, such as to obtain quick payback of investments, with reservoir depletion the result (e.g. The Geysers). An enhanced geothermal system (EGS) study showed that sustainable production can be achieved with lower production rates and can provide similar total energy yields as those achieved with high extraction rates.

Regeneration of geothermal resources following exploitation is a process that occurs over various time scales, depending on the type and size of production system, the rate of production and the characteristics of the resource. It depends directly on the rate of fluid/heat re-supply. Time scales for re-establishing the pre-production state following the cessation of production are examined using numerical model simulations for: 1) heat extraction by geothermal heat pumps, 2) the use of a doublet system on a hydrothermal aquifer for space heating, 3) conventional use of low-enthalpy resources, 4) the generation of electricity on a high enthalpy, two-phase reservoir and 5) an EGS. The results show that after production stops, recovery driven by natural forces like pressure and temperature gradients begins. The recovery typically shows asymptotic behaviour, 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.

It is concluded that: 1) "balanced" fluid/heat production that does not exceed the recharge can be considered fully sustainable, 2) production rates that persistently exceed the rate of recharge (natural or induced) will eventually lead to reservoir depletion, thus stopping economic production, 3) following termination of production, geothermal resources will undergo recovery towards their pre-production pressure and temperature states, 4) the post exploitation recovery typically exhibits an asymptotic behaviour, being strong at the start and slowing subsequently, and reaching a "practical" replenishment (~95% recovery) on time scales of the same order as the lifetime of the geothermal production system, 5) geothermal resources are renewable on timescales of technological/societal systems (~30-300 years), 6) sustainable production secures the longevity of the resource at lower production levels, 7) the level of sustainable production depends on the utilization technology as well as on the geothermal resource characteristics and 8) long-term production from geothermal resources should be limited to sustainable levels.

There is a currently clear need for more research into geothermal production sustainability, with the following investigations identified: 1) determination of "true" sustainable production levels for various geothermal resources and the techniques for defining them at the earliest possible stages of development, 2) compilation and analysis of the cases where stable reservoir performance has been successfully obtained during production, 3) synoptic treatment of numerically modelled production technologies by re-examining the regeneration time scales, 4) numerical modelling of EGS considering long-term strategies and various production scenarios and

5) deriving dynamic recovery factors that account for enhanced regeneration.

One of the aims of this paper is to stimulate discussion of sustainable geothermal energy utilization amongst the geothermal community and the authors encourage and invite comments (send to: mongillom@reap.org.nz before 30 November 2006).

Introduction

Renewability and sustainability are terms often used and discussed. 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 MW_t. 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.

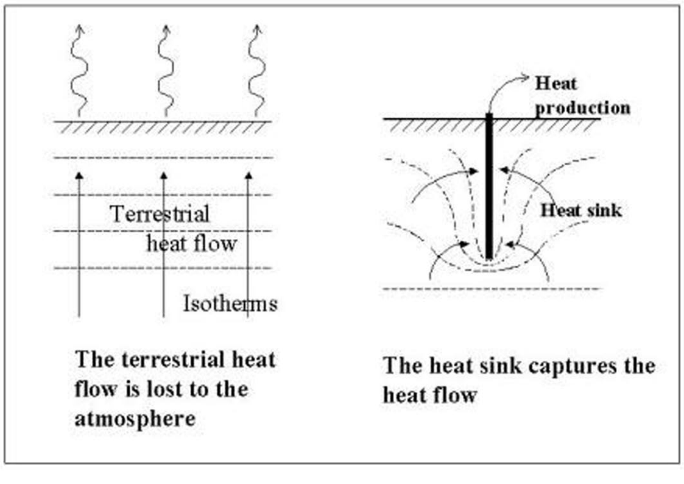

Figure 1. Principle of geothermal heat extraction and production.

Renewability and Sustainability

In general, geothermal energy is classified as a renewable energy resource, hence is included together with solar, wind and biomass alternative energy options in government R&D programs, and is identified as renewable in materials promoting geothermal energy. Renewable describes a attribute of the energy resource, i.e. *the energy removed from a resource is continuously replaced by more energy on time scales similar to those required for energy removal and those typical of technological/societal systems (30-300 years)*, rather than geological times (Axelsson, et al., 2005; O'Sullivan and Mannington, 2005; Rybach, et al., 1999; Stefansson, 2000).

The original definition of sustainable development goes back to the Brundtland Commission Report (1987; reinforced at the Rio 1991 and Kyoto 1997 Summits), where it was defined as:

> *"development that meets the needs of the present without compromising the ability of future generations to meet their own needs".*

In relation to geothermal resources and, especially, to their exploitation, 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 an appropriate production level. A definition of sustainable production from a geothermal system has been suggested recently (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)."*

This definition applies to the total extractable energy (the heat in the fluid plus that 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, and 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).

Effects of Heat/Fluid Production from a Geothermal Reservoir

Geothermal resources are commonly used by withdrawing fluid and extracting its heat content. There are prominent examples that this can happen in a fully sustainable 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, i.e. renewability. 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 as "fully" sustainable. Such production rates are, however, limited and in many cases not economical for utilization.

High production rates can exceed the long-term rate of recharge and can lead, with increasing production duration, to depletion, especially of the fluid content. Most of the heat stored in the matrix however, remains in place. Many utilization schemes (high enthalpy steam and/or water dominated reservoirs, doublets in hydrothermal aquifers), therefore apply reinjection, which at least replenishes the fluid content and helps to sustain or restore reservoir pressure. On the other hand, cold reinjected fluid can create thermal depletion in an increasing volume of the reservoir.

Geothermal resources are often taken into excessive production (of the reservoir fluid as the heat carrier), mainly to meet economic goals like quick payback of investments for exploration and equipment, with reservoir depletion the result. There are numerous examples for this approach worldwide, the most prominent is the vapour-dominated field of The Geysers, California, USA. Figure 2 shows the change of production with time, and the effect of reinjection starting in January 1998. Reinjection halted the production decline only temporarily.

"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-supply. The time scales for re-establishing pre-production states are examined below for five resource types and utilization schemes: 1) heat extraction by geothermal heat pumps; 2) hydrothermal aquifer, used by a doublet system for space heating; 3) conventional use of low-enthalpy resources without reinjection; 4) high enthalpy, two-phase reservoir, tapped to generate electricity; 5) enhanced geothermal systems (EGS). Numerical model simulations were used.

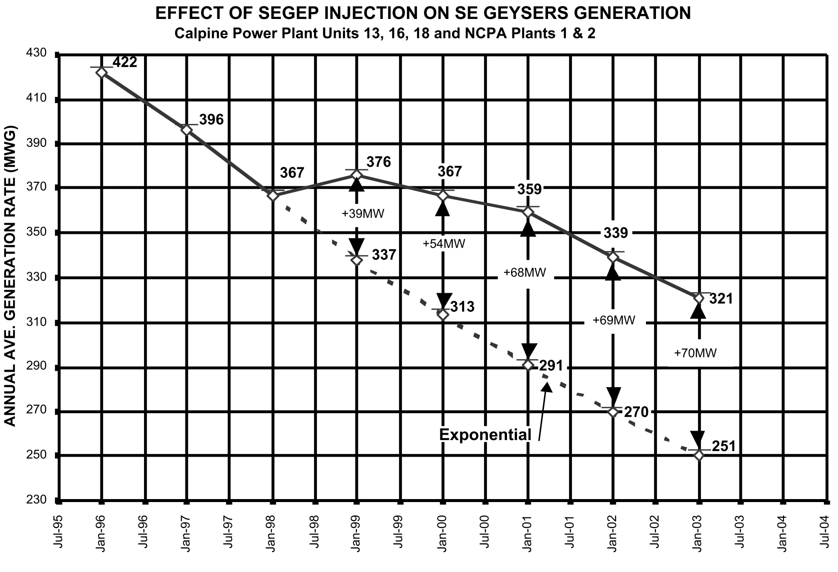

Figure 2. Production decline and reinjection effects at The Geysers (from Bertani, 2005).

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). Here 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 provided 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 re-supply of fluid is secured by the hydrologic cycle (infiltration of precipitation) and the heat comes "from above" (atmosphere) and/or "from below" (geothermal heat flow); the relative proportions depending on aquifer depth. This leads to an approximately constant aquifer temperature throughout the year without any significant seasonal variation. Any deficit created by heat/fluid extraction is replenished by the (lateral) groundwater flow.

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 behaviour 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 iso,therm pattern, with the BHE as its centre (Figure 3). 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

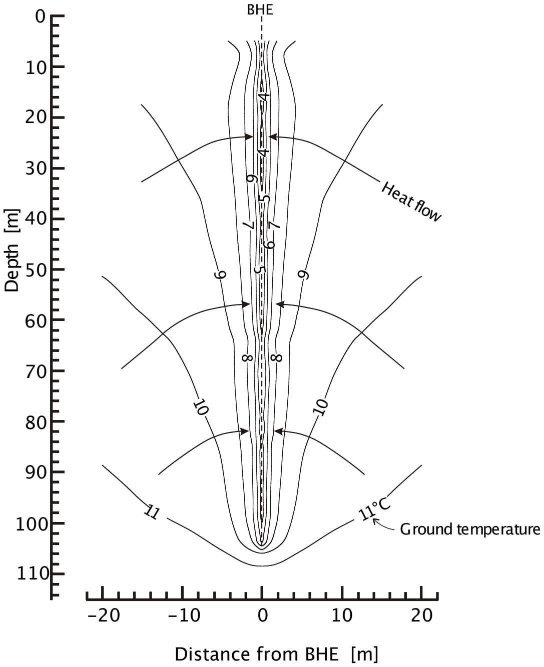

Figure 3. Calculated temperature isolines around a 105 m deep BHE, during the coldest period of the heating season 1997 in Elgg, ZH, Switzerland. The radial heat flow in the BHE vicinity is around 3 W/m^2 (from Rybach and Eugster, 2002).

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).

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 4). Later, the yearly deficit decreases asymptotically. Following 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 behaviour: 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.

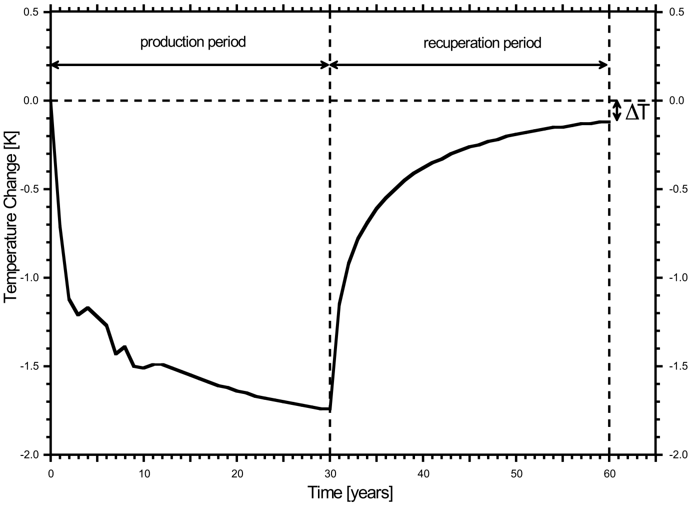

Figure 4. Calculated ground temperature change at a depth of 50 m and at a distance of 1 m from a 105 m long BHE over a production period and a recuperation period of 30 years each (from Eugster and Rybach, 2000).

The results of numerical modelling for a single BHE show 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 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), 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 MW$_t$. 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 fulfils this condition.

The steady state production temperature is not reached even after 300 years. The development of the temperature can be characterised by considering the temperature change ĆT 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 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).

Low-Enthalpy Resources

Conventional use of low-enthalpy resources for heat production, without reinjection, is common, especially in Iceland. The Laugarnes Geothermal Field has been used in this manner for over 75 years. Production was increased by a factor of 10 in the mid-1960s, after more than 30 years of low production with negligible pressure change (Axelsson, et al., 2005). Though this increase resulted in a 12 bar pressure drop, a new "semi-equilibrium" level was reached after about 10 years, where it has remained stable for the last 3 decades. This sustainable production, without reinjection, is the result of enhanced recharge amounting to 10 times the natural state value.

The Hamar Geothermal System, Iceland, is another low-enthalpy (65 °C) example. It has been utilized at 23-42 l/s for the last 33 years, with only a 3 bar pressure decline. A lumped parameter model was used to calculate the effect of 200 years of production at 40 kg/s. The results indicate that >40 kg/s is sustainable with the down-hole pumps located above the current maximum operational depths of 200-300 m. Modelling also shows that, with a conservative system volume of 0.5 km^3, constant production temperature can be maintained for over 200 years. Thus, the sustainable production is >40 kg/s, with a sustainable energy of >11 MW$_t$ (ibid.).

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 uneconomic. 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 showed that pressure recovery occurred much faster than temperature re-establishment. Table 1 shows that the relative recovery increased slowly with time and that it took several times longer than the production duration to reach a reasonable recovery (say 90 %). The recovery rate was strong in the beginning but decreased subsequently, and only after an infinite time was complete recovery reached (asymptotic behaviour). This study contrasts with the two described below in that it used a fixed recharge rate, rather than allowing production enhanced recharge.

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 %

A recent and more realistic study examined the recovery of the Wairakei-Tauhara geothermal system using a well-calibrated computer model based on an extensive database and relatively long production history (>50 years) (O'Sullivan and Mannington, 2005). It assumed a total of 100 years of production at the current rate (~1900 MW$_t$), and a production ratio (pr) of 4.75 based on a pre-exploitation natural energy flow of 400 MW$_t$ (Allis, 1981). The results showed very rapid recovery of pressure (within ~25 years). The temperature recovery was slower, ranging from 50-120 years for 90%-98% recovery over the "deep recharge zone", to 300 years for 90% recovery further away. Vapour saturation recovery was very slow, taking ~300 years to return to the pre-exploitation state. Hence, this detailed model showed that the Wairakei-Tauhara geothermal system recovered to almost its pre-exploitation state in 300 years, or three times the total production period. This result is in good agreement with a lumped-parameter model estimate (*ibid.*): (recovery time) ≈ (pr-1)* (production time) ~3.75 (production time). A contributing factor to this model showing a more rapid recovery rate than that of Pritchett (1998) is that Wairakei-Tauhara has a much higher permeability (horizontal ~200-800 md; vertical ~5-25 md) (Mannington, et al., 2004) than that used by Pritchett.

Another recent example used a comprehensive numerical model that covers the entire Hengill volcanic system, Iceland. It was used to examine the Nesjavellir Geothermal System during 30 years of intense production (540 kg/s), for both direct use heating (200 MW$_t$) and electricity generation (120 MW$_e$), followed by 250 years of recovery (Axelsson, et al., 2005). Preliminary results showed that the pressure recovers on a time scale comparable to that of production. However, the temperature (not well calibrated due to lack of data) recovered much more slowly (>250 years), though the temperature drop at the end of production was only 4-5 °C (~1.5% of the reservoir temperature). Results also indicated that the effects of this intense (excessive) production should be reversible, with sustainable production at a reduced rate possible after the recovery period.

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, 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.

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 behaviour, 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 centre and production well at each corner of a square) with high (1800 t/hr) and low (475 t/hr) production rates was considered (injection flow rate = production flow rate).

Production at the high rate yielded higher power generation capacity at the beginning (45 MW_e). A parasitic load of nearly 10 MW_e 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 5). The total energy produced amounted to 245 MW_eyear.

At the lower circulation rate, the starting capacity was only 12 MW_e (Figure 6), 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 MW_eyear, 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.

Research Needs

Though numerous basic studies of geothermal production sustainability (Axelsson, et al., 2005; 2001; Lovekin, 2000; O'Sullivan and Mannington, 2005; Rybach, 2003; Sanyal, 2005; Stefansson, 2000; Stefansson and Axelsson, 2003; 2005; 2006; Ungemach, et al., 2005; Wright, 1995) have been conducted, the authors strongly believe that there is still a clear need for significantly more research. In particular, specific, focussed investigations are needed in several areas:

- Determination of "true" sustainable production levels for geothermal resources and techniques for defining them at the earliest possible stages of development.
- Compilation and analysis of the successful examples for stabilizing reservoir performance during production for both high enthalpy (Larderello, Italy [Cappetti, 2004];

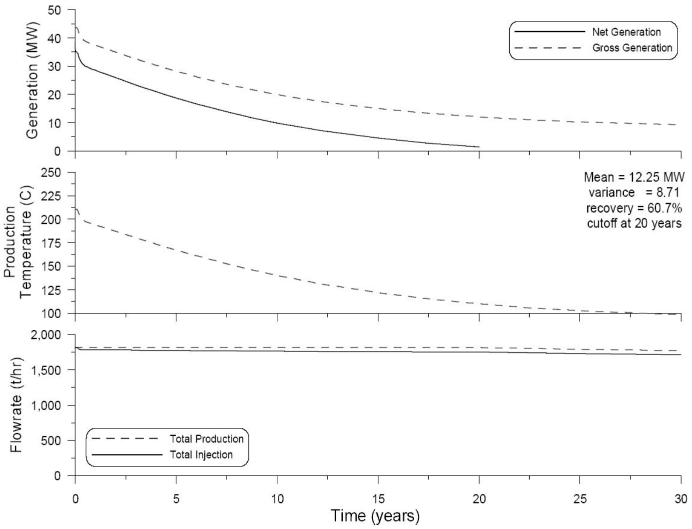

Figure 5. Power generation from an EGS system with high circulation rate (500 l/s) starts with 45 MW_e capacity but terminates after 20 years with a total generation of 245 MW_eyears (from Sanyal and Butler, 2005).

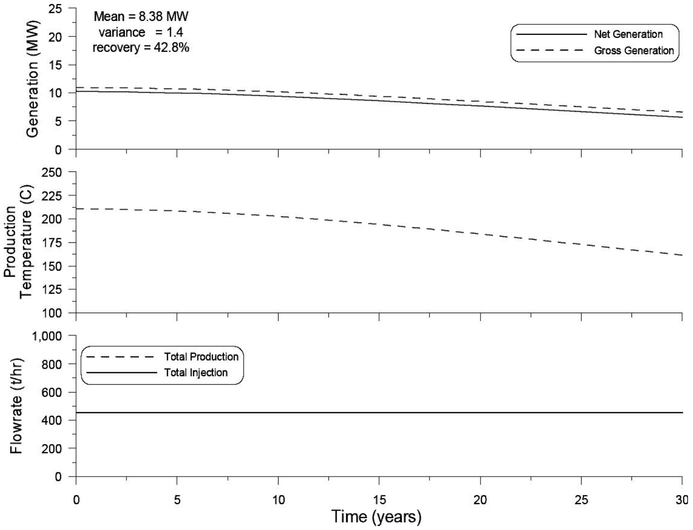

Figure 6. Lower circulation rate (126 l/s) yields long-lasting power production with total generation of 250 MW_eyears (from Sanyal and Butler, 2005).

Kawerau, New Zealand [Bromley, 2006a]; Wairakei, New Zealand [Bromley, 2006b]) and low enthalpy systems (Laugarness, Iceland [Axelsson, et al., 2005]; Paris Basin, France [Ungemach, et al., 2005]).

- Synoptic treatment of numerically modelled production technologies (steam-turbine power plant, geothermal doublet, ground-source heat pump) through a unified approach looking at the regeneration time-scales.
- Numerical modelling of EGS considering long-term production/recovery, by different production scenarios like combined heat and power (CHP) production, load-following operation, etc.
- Determination of "dynamic" recovery factors: these must account for enhanced recharge driven by the strong hydraulic and thermal gradients created by fluid/heat extraction.

Conclusions

- Any "balanced" fluid/heat production by a geothermal utilisation 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 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 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, as stated above.

One of the aims of this paper is to stimulate discussion of sustainable geothermal energy utilization amongst the geothermal community, with a major outcome being the development of an International Energy Agency- Geothermal Implementing Agreement position on this issue. Consequently, the authors encourage and invite comments to be sent to Mike Mongillo (mongillom@reap.org.nz) before 30 November 2006.

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