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How Renewable are Geothermal Resources?

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ABSTRACT

Geothermal resources are utilized by withdrawing the fluid and/or extracting the heat content of a reservoir, which causes depletion. After production stops the re-establishment of the original resource/reservoir conditions begins, by processes driven by natural forces like pressure and temperature gradients. The time-scale of recovery has been addressed by numerical simulations. The recovery times are, for the resource/utilization types considered: 1) high enthalpy, two-phase reservoir, produced to generate electricity—several 100 years; 2) hydrothermal aquifer, used by doublet system for space heating—100–200 years; 3) conductive heat extraction by shallow ground-source heat pumps—roughly the time of production (e.g. practical recovery in 30 years after a 30 years production period). Thus geothermal resources can be considered renewable on time-scales of technological/societal systems and do not need geological times for regeneration as fossil fuel reserves do (coal, oil, gas). Sustainable production can be achieved for types 2) and 3).

Introduction

Geothermal energy is generally considered as being 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. But how exactly – and especially on what time-scale– are geothermal energy resources renewable? This question shall be addressed in the following.

The principal renewal base of geothermal resources is the terrestrial heat flow from the earth's interior. Although this energy flux amounts globally to the impressive figure of 40 million MW_t it must be kept in mind that only a small fraction is acting in populated areas where it could be used in principle. During geologic times a huge amount of thermal energy has been accumulated in the subsurface which is present on one hand in fluid fillings and in the rock matrix on the other. 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 discharge, can be considered as fully renewable.

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 apply therefore reinjection (high enthaply 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.

The production of geothermal fluid and/or heat (schemes see below) successively creates a hydraulic/heat sink in the reservoir which 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 primary aim of the following considerations is to address the time scale of reestablishment. Three resource types and utilization schemes will be treated: 1) high enthalpy, two-phase reservoir, produced to generate electricity; 2) hydrothermal aquifer, used by a doublet system for space heating; 3) conductive heat extraction by shallow ground-source heat pumps.

High enthalpy two-phase reservoir

Resources of this type are widely used to generate electricity. Some of them show strong signs of depletion. Therefore, reinjection schemes are increasingly introduced. Reinjection however can cause temperature decrease in the resource volume;

together with the production rates dictated by economic constraints rather then by balancing the natural resupply, this can limit the productive lifetime of power plants to a couple of decades only.

A thorough theoretical study on the electrical production capacity of a hypothetical reservoir, albeit with realistic operational characteristics, has been presented by Pritchett (1998). The study addresses the changes in electricity generating capacity in time, first during ongoing (continuous) production, and subsequently the recovery after shut-down of the power plant operation.

Figure 1 shows the results of Pritchett (1998): reservoir behaviour during a 50-year production period and during a following recovery phase, indicated by the pressure and temperature development at a monitoring point placed between the production and reinjection wellfields (for details see Pritchett 1998). The change in the total steam volume in the reservoir is also depicted.

Pressure recovery proceeds the fastest, followed by temperature reestablishment. Table 1 shows that the relative recovery increases only slowly with time and that it takes several times longer than the production duration to reach a reasonable recovery (say 90 %). The recovery rate is strong in the beginning but decreases subsequently, and theoretically only after infinite times can complete recovery be reached ("asymptotic behaviour").

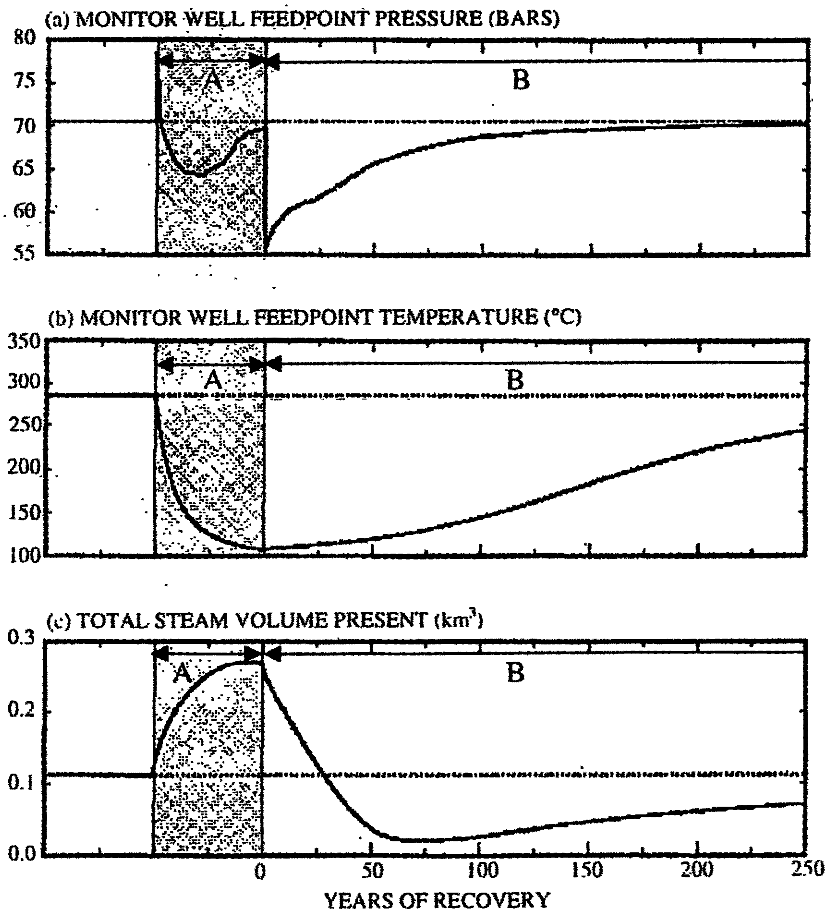

Figure 1. Computed changes in monitor-well feedpoint pressure (a) and temperature (b) and in total voume of steam present in reservoir (c) during 50-year production interval (A) and subsequent reservoir recovery (b). From Pritchett (1998).

Table 1. Relative recovery of a two-phase reservoir after 50 years production (from data in Pritchett 1998).

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

Hydrothermal Aquifer

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

The town of Riehen next to Basel has the first and so far only geothermal based district heating system in Switzerland, with a capacity of 15 MW_t, which supplies about 160 users. About 50% of the needed energy is covered by a geothermal doublet operation (production well 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"). The average flowrate is 10 l/s, at 62°C. Reinjection temperature is 25°C which yields a useable temperature drop of 37 K. The use of geothermal energy and the heat pump started operation in 1994. Since 1998 an extension into the neighbouring German town of Lörrach is under construction.

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 (Mégal 1996).

Table 2. Reservoir recovery from production-recovery cycles of 10, 20 40 years duration.

Operation type	Total operation time [years]	Energy production [GWh]	Energy production [%]	Reservoir recovery [%]
no production breaks, steady temp. drop	80	424	100	0
2x40 year production-recovery cycles	160	429	101.1	20.8
4x20 year production-recovery cycles	160	433	102.0	36.5
8x10 year production-recovery cycles	160	436	102.7	48.7
ideal system with no thermal drawdown	80	448	105.5	100

Additional attention is focussed on the recovery effect of the geothermal doublet operation in Riehen. Numerical simulations for porous and fractured reservoir models have been performed, for production and production break phases of different duration (10, 20, 40 years). Three different FE models have been used for the calculations of the production temperature and thermal recovery: 1) homogeneous porous aquifer; 2) fractured aquifer with a distance between the fracture zones of 50 m; 3) fractured aquifer with a distance between the fracture zones of 100 m. For details see Mégel and Ryback (1999).

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 2). 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 2). For cycles of 20 years the corresponding value is 36.5%, for 40 years 20.8% respectively. Consequently, short production-recovery cycles produce more energy and are therefore more favourable with regard to the geothermal energy utilization.

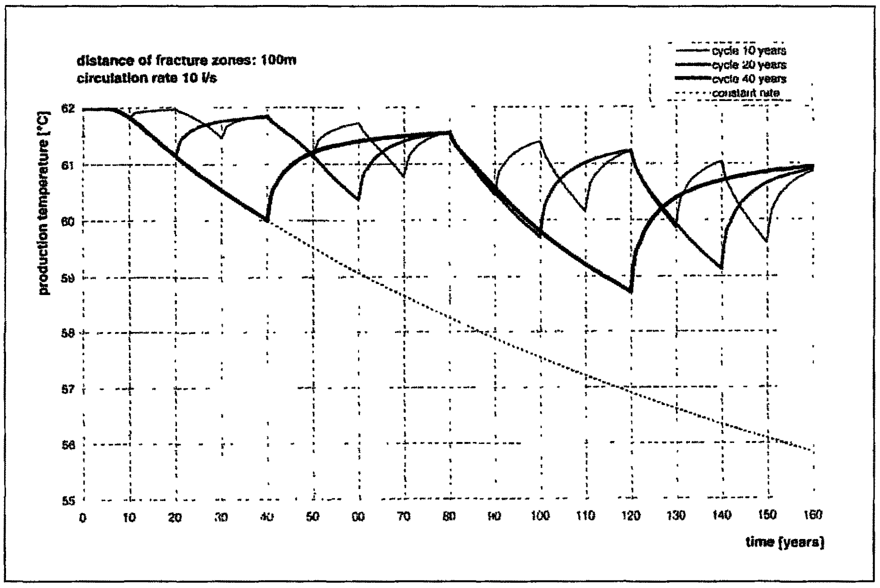

Figure 2. Production temperature for pfoduction-recovery cycles of different duration in a doublet operation (from Mégal and Rybach 1999).

Shallow Ground-Source Heat Pumps

Shallow geothermal resources (< 400 m depth by governmental definition in several countries) are omnipresent. Below 15 - 20 m depth everything is geothermal: the temperature field is governed by terrestrial heat flow and local ground thermal conductivity structure (± groundwater flow). The ubiquitous heat content of shallow resources can be made accessible by artificial circulation like the Borehole Heat Exchanger (BHE) system. The most popular BHE heating system with one or more boreholes typically 50 - 200 m deep is a closed circuit, heat pump (HP)-coupled system, at least in Switzerland (see Rybach and Eugster 1997) where such systems supply 75% of geothermal heating (Rybach 1998).

Extensive measurement campaigns have been performed at a commercially delivered BHE/HP installation in Elgg near Zurich. Object of the campaigns is a single, coaxial, 105 m long BHE, in use since its installation in a single family house. The BHE supplies a peak thermal power of about 70 W per m length (which is higher than normal). The measurement results were used to calibrate a 2D numerical code. Ground temperatures over the first five years of measurement were fitted to within one or two tenths of a degree Celsius. Additionally the formation temperature was predicted for several further years using assumed load profiles. The immediate surroundings of the BHE cools down in the first years and does not fully recover during the system lifetime. The long-term performance stabilizes afterwards, albeit at a somewhat lower but constant level. Thus sustainable production can be achieved on the long term .

The code used (COSOND, in cylindrical coordinates) treats diffusive heat transfer in the ground, advection in the BHE, heat transfer between the BHE fluid and the wall materials, as well as heat transfer between atmosphere and ground. The program flow is controlled by a load profile which contains the atmospheric temperatures and the operational data of the heat pump. The FD model used has 11,700 grid cells in a model volume of $2 \cdot 10^6$ m^3 . Details are given in Rybach and Eugster (1998) and Eugster and Rybach (1999).

Heat extraction over decades causes heat depletion/temperature decrease in a certain volume of the ground. After termination of BHE operation thermal recovery beings. Different simulation runs have been performed with different operation durations. During the production period of a BHE, the draw-down of the temperature around the BHE is strong during the first few years of operation. Later, the yearly deficit decreases asymptotically to zero. After shut-down of heat extraction, regeneration of the ground begins. During the recuperation period after a stop-of-operation the ground temperature shows a similar behaviour: during the first years, the temperature increase is strong and tends with increasing recuperation time asymptotically to zero. These effects are shown in Figure 3.

The time to reach a practically complete recovery depends on how long the BHE has been operational. Principally, the recuperation period equals nearly the operation period. This is shown in Figure 4 for different distances from the BHE and for different final temperature deficits.

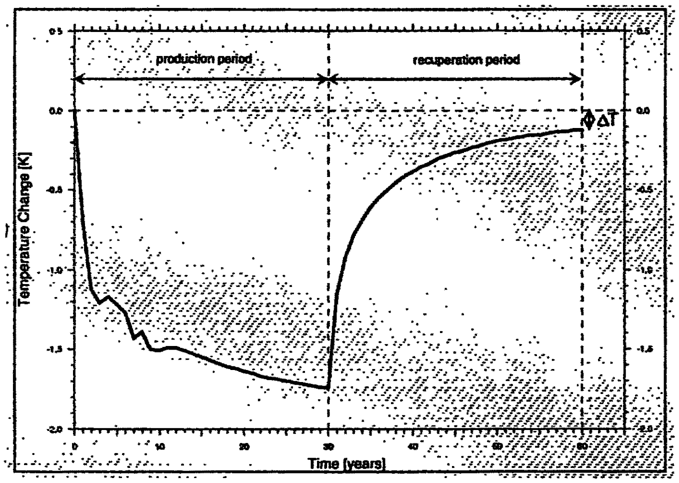

Figure 3. Calculated temperature change in a depth of 50 m and in a distance of 1 m from the BHE over a production period and a recuperation period of 30 years each (from Eugster and Rybach 1999).

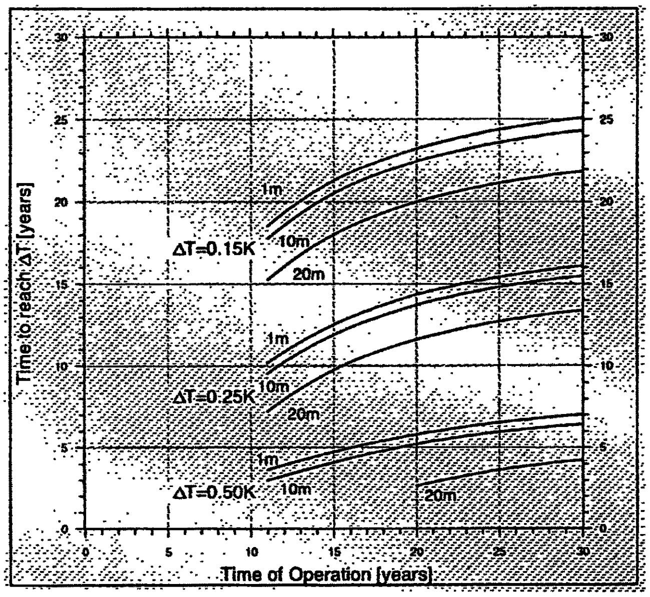

Figure 4. Duration of the recovery period to reach a final temperature deficit (ΔT, see Fig. 2) of 0.5, 0.25 and 0.15K for different radial distances from the BHE as a function of the time of operation (from Eugster and Rybach 1999).

Conclusions

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

- for a high-enthalpy reservoir (utilised for electricity generation) sufficient recovery needs several 100 years;
- for a doublet system (district heating) it takes 100 – 200 years;
- for shallow, decentral heat pump system the recovery time roughly equals the time of production (e.g. practical recovery in 30 years after a 30 years production period).

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). Besides, for the doublet and heat pump systems, sustainable production can be achieved.

Acknowledgements

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