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Geothermal energy: sustainability and the environment

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Abstract

Geothermal resources can be considered renewable on the time-scales of technological/societal systems and do not require the geological times of fossil fuel reserves such as coal, oil, and gas. The recovery of high-enthalpy reservoirs is accomplished at the same site from which the fluid or heat is extracted. Moreover, truly sustainable production can be achieved in doublet and heat pump systems. Generally the environmental impacts of geothermal power generation and direct use are minor, controllable, or negligible. There must be full compliance with environmental regulations, which may vary from country to country. In any case the effects must be monitored and documented (often over long periods), rated and, if necessary, reduced.

Keywords: Resource recovery; Sustainability; Environmental effects; Legislation

1. Introduction

Geothermal energy is usually referred to as a renewable source of energy and as such is listed with solar, wind and biomass as alternative energy options in governmental R & D programs, in materials promoting geothermal energy, etc. It is also termed as environmentally friendly, by virtue of the particularly low emissions of greenhouse gases into the atmosphere. Both attributes are indeed applicable, but within certain limits, which must be addressed in a fully objective manner. Any attempts at disguising or even concealing production decline or a possible impact on

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the environment could bring discredit upon an entire industry, spreading mistrust amongst the authorities as well as the general public (as in the case of nuclear energy).

2. Sustainability

The original definition of sustainability dates 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 utilisation for energy purposes, sustainability means the ability of the production system to sustain production levels over long periods. Often the resources are put into production (with the reservoir fluid as heat carrier) with the main objective of meeting economic goals, in other words, a quick payback of the investment costs of exploration and equipment, with the result that the reservoir is swiftly depleted (Fig. 1). There are numerous examples of this approach worldwide, the most prominent being the vapour-dominated field of The Geysers, USA. In contrast, sustainable production of geothermal energy secures the longevity of the resource, at a lower production level.

Geothermal resources are customarily exploited by withdrawing the fluid and extracting its heat content. There are many important examples of how this can be accomplished in a totally renewable way: thermal springs in many parts of the world

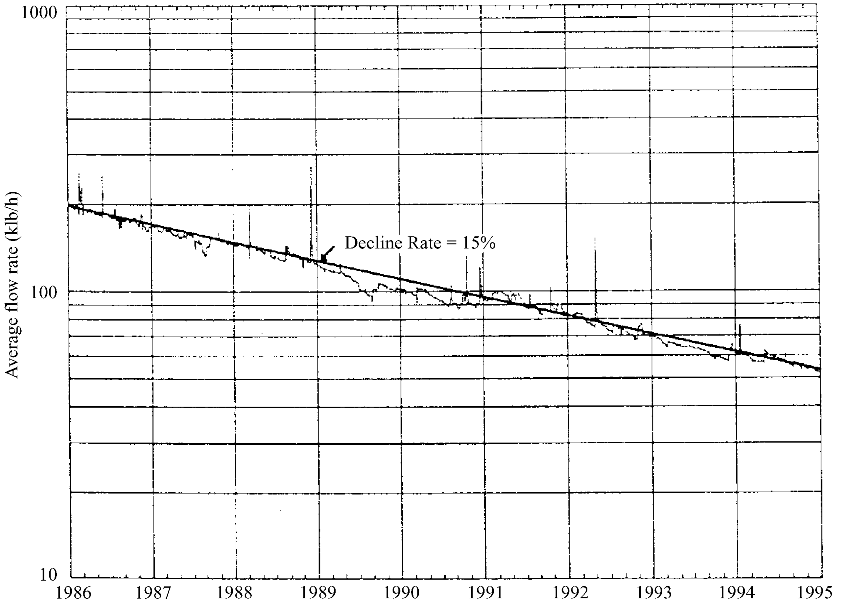

Fig. 1. Example of 150% production decrease over 10 years in the steam reservoir at Calistoga, USA (average daily flow rate versus time; from Sanyal et al., 2000).

have been producing impressive amounts of heat (and fluid) on the surface for centuries, without showing any signs of decline. In such situations a balance obviously exists between surface discharge and fluid/heat recharge at depth. Any "balanced" production of fluid/heat in a geothermal utilisation scheme, i.e. which does not produce more than the natural discharge, 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 eventually lead to depletion of the resource, in particular of the fluid, whereas the heat stored in the matrix remains to a large extent in place. Many utilisation schemes have therefore resorted to reinjection (the high enthalpy steam and/or water-dominated reservoirs, doublets in hydrothermal aquifers), which at least replenishes the fluid content and helps to maintain or restore reservoir pressure. The cold reinjected fluid may, however, lead to temperature decreases in increasingly large volumes of the reservoir.

Extraction of geothermal fluid and/or heat subsequently creates a hydraulic/heat sink in the reservoir. This leads to pressure and temperature gradients that, after extraction ends, generate an influx of fluid and heat to re-establish the pre-production state.

Numerical simulations have been devised to determine the time-scale of recovery for the main utilization schemes (high-enthalpy reservoir for power generation, aquifer-based doublet, geothermal heat pumps) (Rybach et al., 2000). Recovery exhibits an asymptotic behaviour, strong at the beginning and then slowing down, with recovery of the original state attained theoretically only after infinite time. However, practical replenishment (e.g. 95% recovery) will be achieved much sooner, generally on a time-scale of the same order as the lifetime of geothermal production systems.

- In the case of a high-enthalpy reservoir (utilised for electricity generation) recovery, to be fully adequate, will take a few hundred years, depending on local recharge conditions (Table 1).
- In a doublet system (district heating) recovery will take 100–200 years (Mégel and Rybach, 2000).
- In a shallow, decentralized heat pump system, in the heating-alone mode, the recovery time roughly equals the length of production (e.g. practical recovery in 30 years after a 30-year period of production; Fig. 2). For geothermal heat pumps in the heating/cooling mode, recovery takes place during the yearly cycle.

Table 1
Relative recovery of a two-phase reservoir after 50 years of production (Pritchett, 1998)

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

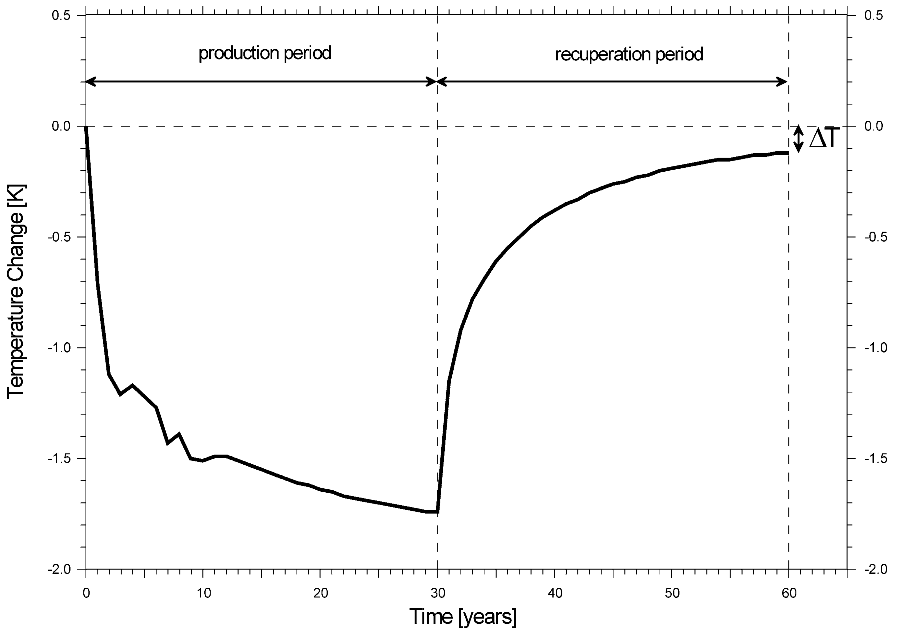

Fig. 2. Calculated temperature change within a depth of 50 m and a distance of 1 m from a borehole heat exchanger, over a production period and a recovery period of 30 years each (Rybach and Eugster, 2002)—after 30 years recovery is almost total ($\Delta T = 0.1$ °C).

3. Environment

Protection of the environment is one of our most important obligations, whose goals were defined during the United Nations Summits in Rio (1991), Kyoto (1997) and Johannisburg (2001). Any type of energy production will have some impact on the environment, but the degree or extent of this impact will depend on the technology used. Both of the main geothermal applications, power generation and direct use, can have an effect on the environment. These need to be identified, quantified and, if necessary, eliminated or abated, at the very least in order to comply with environmental regulations.

3.1. Power generation

Whatever the technology applied (which is mainly dictated by the properties of the geothermal fluid), the main phases of development and production are:

- exploration;
- production tests; and
- construction and operation.

The environmental effects may be temporary or irreversible and include:

- changes to landscape, land use;
- emissions into the atmosphere, surface and subsurface waters;
- noise;
- land subsidence, seismicity; and
- solid waste.

Geothermal power generation creates a much lower emission of greenhouse gases than most other technologies. In any comparison it is important that we consider the entire production cycle, i.e. all phases before, during and after power plant operation. Geothermal power plants have particularly low CO_2 emissions compared to other technologies; where CO_2 abatement is concerned, they are therefore more attractive options for power generation than coal, oil or gas (Fig. 3).

Environmental effects cannot be excluded during geothermal power generation. These will differ according to the characteristics of the site, reservoir and power plant. Binary type power plants (i.e., a closed system in which a working fluid drives the turbine, not the geothermal steam or fluid) have by far the smallest impact, except for waste heat (Fig. 4).

3.2. Direct use

In principle, the environmental impacts of direct use are the same as with power generation, but the degree to which utilization affects the environment is proportional to its scale. As the various phases of direct utilizations are on a smaller scale and the fluid extracted is considerably less than in power generation, the environmental effects of direct uses are correspondingly smaller. Possible effects are listed in Table 2.

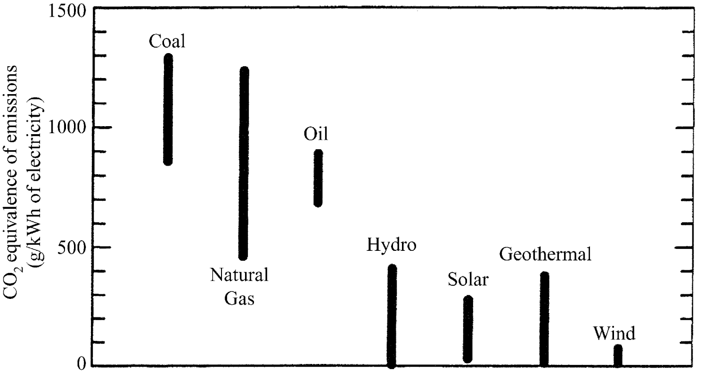

Fig. 3. Greenhouse gas emissions (CO_2 equivalent) of different power generation technologies (Hunt, 2001).

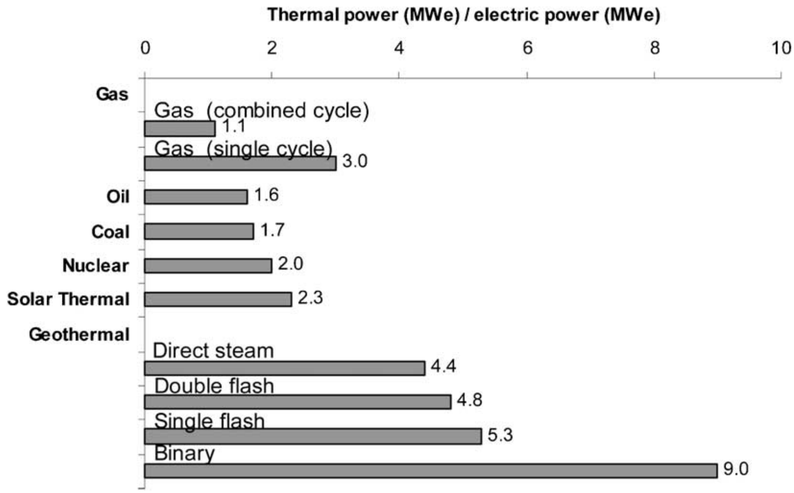

Fig. 4. Waste heat from various power generation systems. Due to its low conversion efficiency, geothermal binary power plants release relatively large amounts of heat. Co-generation or cascaded direct use of the waste heat is therefore recommended (DiPippo, 1991).

3.3. Seismicity

As reinjection becomes more frequent (see below), induced seismicity becomes more of an issue than ever. In reinjection, large volumes of spent geothermal fluids are injected under pressure back into the subsurface, thus changing the pore pressure conditions and the local stress field. Experience shows that increasing volumes of fluids do not lead to larger earthquakes, but more frequent events. Induced seismicity is especially relevant for the Hot Dry Rock technology, where artificial reservoirs are created by hydraulic fracturing, which can induce earthquakes up to a magnitude of $M = 2.0$–3.0 (Rybach, 2002). It is essential that a seismometer network be set up to monitor local seismicity, well before reinjection/fracturing begins.

4. Future trends

Future production schemes are likely to be based on considerations of sustainability, environmental protection and careful resource management, adopting low production rates that can be sustained over long periods of time. Fluid reinjection is an increasingly popular option, as well as cascaded use, where the resource is utilised in steps of ever-decreasing temperature: e.g. industrial applications → space heating → agricultural use → balneology → fish farming.

Legislation for environmental protection during geothermal development is at various stages in a number of countries. The legal requirements apply to all phases, from exploration through production to decommissioning. Nevertheless there is a common trend when addressing the environmental impact of the various development

Table 2
Potential environmental impacts of direct use geothermal projects; probability and severity (Lunis, 1989)[a]

Impact	Probability of occurring[b]	Severity of consequences[b]
Air pollution	L	M
Surface water pollution	M	M
Underground pollution	L	M
Land subsidence	L	L to M
High noise levels	H	L to M
Well blowouts	L	L to M
Conflicts with cultural and archeological features	L to M	M to H
Socioeconomic problems	L	L
Solid waste disposal	M	M to H

[a] Pollution can be chemical and/or thermal.
[b] L = low; M = medium; H = high.

phases; the possible direct or indirect, short-term and long-term, reversible and irreversible effects must all be evaluated beforehand and, in order to comply with regulations, mitigation or avoidance strategies must be adopted. There is an urgent need to standardize the many different geothermal environmental protection laws, e.g. by adopting uniform EU guidelines.

5. Conclusions

Geothermal resources can be considered renewable on the time-scales of technological/societal systems and do not require the geological times of fossil fuel reserves such as coal, oil, and gas. The recovery of high-enthalpy reservoirs is accomplished at the same site from which the fluid or heat is extracted. Moreover, truly sustainable production can be achieved in doublet and heat pump systems.

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