THE SUSTAINABILITY OF PRODUCTION FROM GEOTHERMAL RESOURCES

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INTRODUCTION

In the strictest sense, the sustainability in consumption of a resource, of whatever kind, is dependent on its initial quantity, its rate of generation and its rate of consumption. Consumption can obviously be sustained over any time period in which a resource is being created faster than it is being depleted. If the rate of consumption exceeds the rate of generation, consumption can, nevertheless, be sustained over some time period dependent upon the initial amount of the resource available when consumption begins.

The term "sustainable development" was used by the World Commission on Environment and Development in a somewhat different way, to mean development that "meets the needs of the present generation without compromising the needs of future generations" (Brundtland Commission, 1987). To meet the Brundtland Commission's definition of sustainability for energy supply, we must consider the interactions among all available and reasonably foreseen energy sources. If one resource becomes depleted, we need only have an available substitute to ensure that future generations are able to meet their needs. Kozloff and Dower (1993) believe that whether or not consumption of a resource can said to be renewable depends on the time frame under consideration. They suggest that a perspective of 300 years or more of continuous production is adequate for an energy fuel to be considered as renewable, since technical advances during that time will have rendered today's perspective obsolete.

FACTORS AFFECTING HYDROTHERMAL SUSTAIN ABILITY

The total available amount of heat in any particular hydrothermal geothermal resource and its rate of resupply by conduction and fluid recharge from great depth are quantities potentially amenable to determination by geoscientific methods. The rate of consumption of the resource through production of geothermal fluids at the surface is most strongly dependent on financial, political, and regulatory factors, which we will together term "economic factors." Determination of the potential sustainability of production from a given hydrothermal resource therefore depends on both geoscientific and economic factors, and these factors can, in principle, all be determined.

INTRUSION AND COOLING OF PLUTONS IN THE EARTH

Intrusion of molten igneous rocks into shallow regions of the earth's crust (2 to 10 km depth) has occurred since the beginning of geologic time. Igneous intrusion brings up enormous quantities of heat from mantle depths and deposits this heat in the crust. There is little doubt that the larger, higher-temperature, and more vigorous hydrothermal systems are driven by igneous heat sources.

Numerical model studies of the cooling of magmatic-hydrothermal systems have been carried out by several investigators (Cathles, 1977, 1981; Norton, 1982; Cathles et al., 1997). Such studies as these allow their authors to reach several conclusions: (1) small intrusions can generate large surface heat fluxes and substantial reservoirs of hot rock with vapor- or liquid-dominated hydrothermal reservoirs; (2) the duration of the high surface heat flux, although short geologically, ranges from 5,000 to more than 1,000,000 years; and, (3) enormous volumes of water circulate through the system, with the most vigorous fluid convection taking place underground prior to arrival of the thermal anomaly at the surface.

These numerical modeling results are borne out by radioactive dating of the duration of hydrothermal activity. For example, Sims and White (1981) concluded that hydrothermal activity responsible for deposition of mercury at the Sulphur Bank mine, near The Geysers geothermal field, California, began 34,000 years ago and continues at the present time. White (1968) estimated that a magma volume of 100 km^3 must have been cooling and crystallizing for 100,000 years to supply the convective heat losses at Steamboat, Nevada, at their present rates. The oldest hot spring sinter at that location was deposited 3 m.y. ago, documenting a very long history of hydrothermal activity, perhaps spawned by individual episodes of intrusion to shallow depth from a very large underlying magma body. Silberman (1983) suggested that "the most conclusive data from volcanic-hosted precious-metal vein and disseminated deposits, thermal spring systems, and porphyry-copper deposits suggest that on average, the total time span of hydrothermal activity is about 1 m.y., although the range of activity is between 0.6 and 2.5 m.y."

While all of these results are interesting and pertinent, the most important finding from our perspective is that the duration of typical hydrothermal systems ranges upward from 5,000 to more than 1,000,000 years. System duration depends on the amount of thermal energy input to the crust by the pluton, the permeability of the pluton and host rock, and whether or not free flow out the top surface occurs, among many other variables. High permeability and free flow out the top promote more vigorous fluid circulation and lead to shorter system lifetimes. We conclude that hydrothermal systems in the earth's crust meet any reasonable definition of the terms "renewable" and "sustainable". However, exploitation that exceeds natural recharge can greatly shorten the system lifetime.

Estimates of the rate of natural recharge of a system are available from two sources. The undisturbed natural system will produce a heat-flow anomaly at the earth's surface which, if defined well enough, may be integrated over its surface area to yield the natural rate of conductive heat loss from the top of the resource. To such determinations must be added the heat lost from hot springs, geysers and other surface features. This total heat loss at the surface is taken to equal the rate of heat input from deep convective and conductive thermal resupply. A second method of determining natural recharge rate is with detailed reservoir-simulation models. Starting from a known or assumed natural, pre-production state, these models attempt to match either (1) the known, pre-production temperature and pressure distribution in the subsurface, (2) the production history from available wells, or (3) both. The natural recharge rate is included as a parameter to help improve the model match to the field data. When a satisfactory match is achieved, the recharge parameter is taken as an estimate of the natural advective thermal recharge rate. A brief summary of published recharge values (Wright, 1995) indicates that the rate of natural recharge of known crustal hydrothermal systems ranges from a few megawatts to more than 1,000 MWt. The natural recharge rate represents the minimum rate at which hydrothermal systems could, in principal, be produced for thousands of years. However, when artificial production becomes intense, profound changes are made to the natural hydrothermal system and the lifetime may be considerably foreshortened.

ENERGY PRODUCTION FROM HYDROTHERMAL SYSTEMS

Hanano et al. (1990) give a helpful discussion of reservoir longevity for liquid-dominated systems. They use a simulation technique composed of a reservoir model, a well-flow model, and a system-management model to study reservoir pressure and temperature behavior in various development cases. Reservoir behavior is simulated under conditions of constant power-plant electric output, requiring a variable flow rate through periodic addition of new wells as temperature and pressure decline until abandonment conditions are reached. As might be expected, total recoverable electric energy and reservoir longevity are both highest at small output rates. As the power-plant size increases, both parameters decline rapidly. In their example, the system longevity for 1 MWe is almost 200 times greater than for 100 MWe, and the recoverable electric energy from 1 MWe steady production is twice as large as that of 100 MWe. The authors state that six factors strongly influence longevity -- (1) output power, (2) well density, (3) injection strategy, (4) initial reservoir pressure, (5) initial fluid temperature, and (6) permeability in and around the reservoir. The first three factors can be managed artificially, but the last three are fixed by nature and are specific to the area. Economic and engineering influences affect the first three factors, with economics having perhaps the most profound consequences.

ECONOMICS AND SUSTAINABLE DEVELOPMENT

Traditional methods of economic analysis were inherited from an era when the carrying capacities of the earth's natural systems were large compared with the demands being made upon them. Today, this is no longer the case, and new methods of economic analysis are badly needed. In conventional analysis of projects, economists traditionally apply a discount rate to determine the present value of a future asset, say an income stream from geothermal production. When this is done for the relatively long time periods of interest in sustainability, the present value of future geothermal production becomes very small. For example, the present value of $1,000 available 30 years hence discounted at a rate of 10% is $57. If discounted over 100 years, the same $1,000 is worth a mere $0.07 today. According to this method of valuing a future asset, there is little economic incentive for a geothermal developer to extract energy from a resource in a sustainable way.

Pearce and Warford (1993) have introduced the concept of total economic value (TEV) as a way of bringing environmental and sustainability concerns into economic analyses on a project basis. The total economic value for a resource would consist of the direct-use value, the indirect-use value, the option-use value, and the intrinsic or existence value. Direct-use values for energy resources are fairly straightforward, and are given by current economic analysis if these analyses include external costs of using the resource. Indirect-use values consist mainly of values given by ecologists, and are important but may be difficult to quantify for energy resources. Option-use values relate to the amount that governments or individuals are willing to pay to conserve a resource for future use. Existence values relate to all other valuations of the natural asset, such as scenic beauty. The total economic value offers a comprehensive framework within which to value natural assets such as geothermal energy resources. If a system of analysis based on the TEV were implemented, it would be a significant departure from traditional economic analyses of geothermal resources and contribute to a more sustainable rate of production from them. However, much remains to be learned and accepted by governments and markets before modified systems of national accounts and project analysis will be adopted that take the sustainability of the natural environment into full consideration.

GEOTHERMAL ENERGY AND SUSTAIN ABILITY

Sustainable development in the context of the Bundtland Commission (1987) does not imply that any given energy resource needs to be used in a totally sustainable fashion, but merely that a replacement for the resource can be found that will allow future generations to provide for themselves in spite of the fact that the particular resource has been depleted. Thus, it may not be necessary that any specific geothermal field be exploited in a sustainable fashion. Perhaps we should direct our geothermal sustainability studies toward reaching and then sustaining a certain overall level of geothermal production at a national or regional level, both for electrical power generation and direct-heat applications, for a certain period, say 300 years, by bringing new geothermal systems on line as others are depleted.

In this context, we should consider the extent of geothermal resources potentially available. The geothermal energy resource base is known to be very large. Table 1 shows an assessment of the geothermal resource base, which I recently compiled from analysis of many sources, compared with an estimate of oil reserves.

We are drawn to conclude that production of useful levels of energy from geothermal resources can be expected to be undertaken by humans for hundreds or thousands of years. If carefully managed, geothermal production can be sustained essentially indefinitely. New methods of economic analysis that account for the total economic value of a resource would help foster sustainable use of individual resources.

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Table 1. Estimate of World Geothermal Energy Resource Base

GEOLOGIC REGIME	U.S. RESOURCES Joules bbl oil equivalent	WORLD CONTINENTAL RESOURCES[1] Joules bbl oil equivalent	TECHNOLOGY NEEDED FOR DEVELOPMENT
Magmatic Systems (surface to 10 km)	1×10^{24} $160{,}000 \times 10^{9}$	15×10^{24} $2{,}400{,}000 \times 10^{9}$	Hydrothermal (part) EGS[2] (part)
Crustal Heat[3] (3 km to 10 km)	14×10^{24} $2{,}300{,}000 \times 10^{9}$	490×10^{24} $79{,}000{,}000 \times 10^{9}$	EGS
Thermal Aquifers	55×10^{18} 9×10^{9}	810×10^{18} 130×10^{9}	Hydrothermal
Geopressured Basins (surface to 6.9 km)	0.17×10^{24} $28{,}000 \times 10^{9}$	2.5×10^{24} $410{,}000 \times 10^{9}$	Oil Field plus Hydrothermal
Total Oil Reserves[4] (for comparison), bbl	890×10^{9}	$5{,}300 \times 10^{9}$	

1. Excluding Antarctica. Only a rough estimate is possible.
2. EGS = Enhanced Geothermal Systems (a.k.a., Hot Dry Rock).
3. Excluding heat in magmatic systems, thermal aquifers, and geopressured basins.
4. Includes crude oil, heavy oil, tar sands, and oil shale.

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