SUSTAINABILITY OF GEOTHERMAL ENERGY UTILIZATION

by

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ABSTRACT

Growing worldwide population and expanding economic development are causing increased stress on the natural environment. There is a rising international awareness that we must make future development sustainable or risk catastrophic deterioration of the environment. The sustainability of production from geothermal resources is a topic that has received almost no study, leaving the question open to conjecture. As geologic phenomena, hydrothermal systems in the continental crust can be shown to persist for tens of thousands of years. However, system lifetimes can be foreshortened by artificial production at the surface during geothermal energy extraction. Geothermal project feasibility studies typically deal only with developing a certain sized power plant to be run for an arbitrary period, usually 30 years. Such limited studies fail to capture a true measure of the useful energy that can be produced from a geothermal resource.

The International Energy Agency (IEA) is considering coordinating work to provide public information on the sustainability of production from geothermal reservoirs. The objective of this work would be to study important facets of the production of energy from geothermal resources with the view of determining the long-term economic sustainability of such production.

INTRODUCTION

As the world's population increases and nations attempt to further their social and economic development, an increasing level of stress is being placed upon the natural environment. To cope with rising rates of natural-resource consumption and spiraling levels of environmental damage, governments and institutions worldwide are becoming more and more interested in how their finite resources can be deployed to ensure an acceptable future for the human race. They are striving for ways to ensure the sustainability of our atmospheric, hydrologic, mineral-resource, energy-resource, biological, social, and economic systems (Brown et al., 1990; Gore, 1993; McLeod, 1995; Serageldin and Steer, 1994).

Availability of adequate energy supplies at acceptable costs is prerequisite to social and economic progress. In past decades, there was concern that fossil fuels were being depleted too quickly. Today, however, the primary concern in using fossil fuels is environmental degradation. We have found economic ways to curtail emissions of sulfur and nitrogen oxides resulting from fossil-fuel combustion, but we lack technology for economically eliminating carbon dioxide emissions. Non-carbon fuels will be needed to avert a major environmental crisis if an unacceptable amount of greenhouse warming eventually proves to be resulting from the well-documented buildup of CO_2 in the atmosphere. Despite the enormity of this potential problem, generating plants using fossil fuels are being built at increasing rates worldwide.

Accelerated commercialization of renewable-energy resources is an option being promoted by a growing segment of society. The reasons are well known — renewable-energy resources: (1) have environmental advantages over other energy sources; (2) are available locally, mitigating the costs and many other problems of importing, moving fuel minerals around the globe, and maintaining security of supply; and, (3) are supported by enormous resource bases. However, under present systems of economic analysis and compensation, renewable energy resources will not be able to satisfy even new demand for energy in the foreseeable future, let alone replace existing fossil and nuclear uses. In the decades to come, when energy use must rise dramatically in order to support economic growth for a growing population, we must find significantly better ways to obtain and use energy resources.

DEFINITIONS OF RENEWABLE AND SUSTAINABLE

The term "sustainable development" was used by the World Commission on Environment and Development (the Brundtland Commission) 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 be 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. Kozloff (personal communication, 1994) has stated that the biggest problem he perceives in assessing the potential contribution of geothermal energy to society is not so much the lack of knowledge of resource occurrences, but rather the lack of information on the sustainability of production from these resources at useful rates.

In this paper, we will use the term "renewable" to indicate geothermal energy use at the rate of natural recharge of the thermal system. We will consider the term "sustainable" to have a time connotation, as suggested by Kozloff and Dower (1993), and will also use this term in the sense of the Brundtland Commission (1987) to indicate use that does not jeopardize future generations.

GEOTHERMAL ENERGY AND SUSTAINABILITY

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 total available amount of heat in any particular hydrothermal 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.

Duration and Recharge of Natural Hydrothermal Systems

Some studies have been done to understand the duration of natural hydrothermal systems. 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 intrusions 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." These results are corroborated by numerical modeling studies carried out by several people. Some of the original work in this field was done by Cathles (1977, 1981) and by Norton (1982).

The most important findings from these studies is that the duration of typical hydrothermal systems ranges upward from 5,000 to more than 1,000,000 years. Duration depends on the amount of thermal energy input to the crust by the underlying 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.

Natural Recharge of Hydrothermal Reservoirs

Estimates of the rate of natural recharge of a hydrothermal 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 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. The total heat loss at the surface is taken to equal the rate of heat input from deep convective and conductive thermal resupply. As an example of this method, Chapman determined that the undisturbed rate of heat loss from the Roosevelt Hot Springs, Utah, system is 70 MWt, comprised of 60 MWt supplied from the source at depth and 10 MWt supplied from background heat flow, local hydrologic recharge, and exothermic clay alteration reactions (Ward et al., 1978).

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. For example, recent reservoir studies have been performed on Roosevelt Hot Springs, Utah (Yearsley, 1994; Faulder, 1991).

Yearsley's work addressed the remaining potential of the field in terms of capacity versus sustainability. Through matching the production history of the wells in the field using the Tetrad software, he concluded that: (1) the deep fluid recharge is about 23 kg/s at 260o C (26 MWt), although he stated that this might be underestimated since a recharge rate of 37 kg/s (42 MWt) was needed to match the recovery rate of well 25-15 during a three-month shut-in; and, (2) the power decline for various rates of power production indicate an ultimate (sustainable?) capacity of 40 MWe.

Other estimates of natural recharge rates and limited ideas of reservoir longevity for liquid-dominated systems have been provided by various authors. Sakagawa et al. (1994) matched the pre-exploitation temperature and pressure distribution in the Mori field, Hokkaido, Japan using recharge of 35 kg/s at a temperature of 290°C. This yields 45 MWt for the convective thermal input to the system. This field has been under production since 1982 with a 50 MWe plant. According to Elder (1981), the surface heat loss of 1,000 MWt from the Wairakei system in its native state requires a recharge of 600 kg/s of 355o C fluid from depth.

A quick summary of such studies (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. For comparison, Lowell et al. (1995) report that individual vents on the sea floor have typical discharge temperatures of 350°C and outputs of about 1 MWt. Vent fields have typical outputs of 100 to 5,000 MWt, but megaplumes of a few day's duration are postulated with total energy outputs of 1016 to 1017 J. The natural recharge rate represents the minimum rate at which hydrothermal systems could, in principal, be produced for thousands of years.

From these considerations, we can 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.

Exploitation and Sustainability

Hanano et al. (1990) give a particularly instructive illustration of the effect of various production rates on the sustainability of a hypothetical hydrothermal resource. They assumed a field of a certain size, with production coming from a specific block of land and injection going to an adjacent block. Boundary conditions were constant temperature and pressure. Figure 1 illustrates schematically one run of the model. Reservoir pressure draws down as soon as production starts, then its rate of decline slows. Decline of fluid temperature is small at first, but accelerates gradually with time because of migration of injected water into the production well field. Steam quality decreases with temperature, so that the total production rate must be

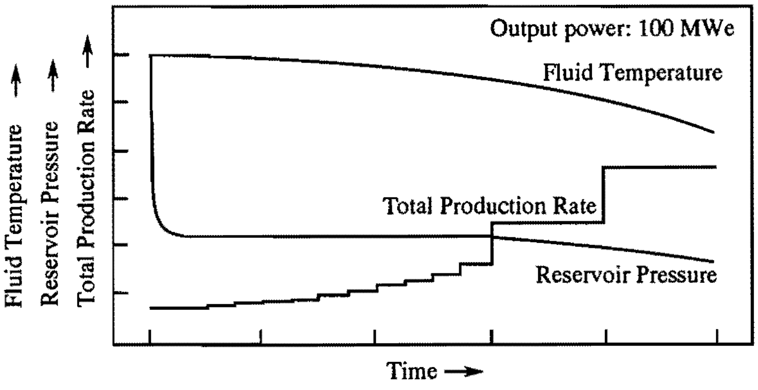

Figure 1. Temperature and pressure behavoir of the reservoir, and increasing produciton rate needed to meet 100 MWe constant power output (after Hanano et al., 1990).

increased to maintain a specified output. As the production rate is increased, pressure declines further. Figure 2 shows the field longevity until abandonment as a function of output power, and Figure 3 shows the recoverable electric energy over the system lifetime as a function of output power. 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 this example, the system longevity for 1 MWe is almost 200 times greater than for 100 MWe, and the recoverable electric energy from 1 MWe is twice as large as that of 100 MWe.

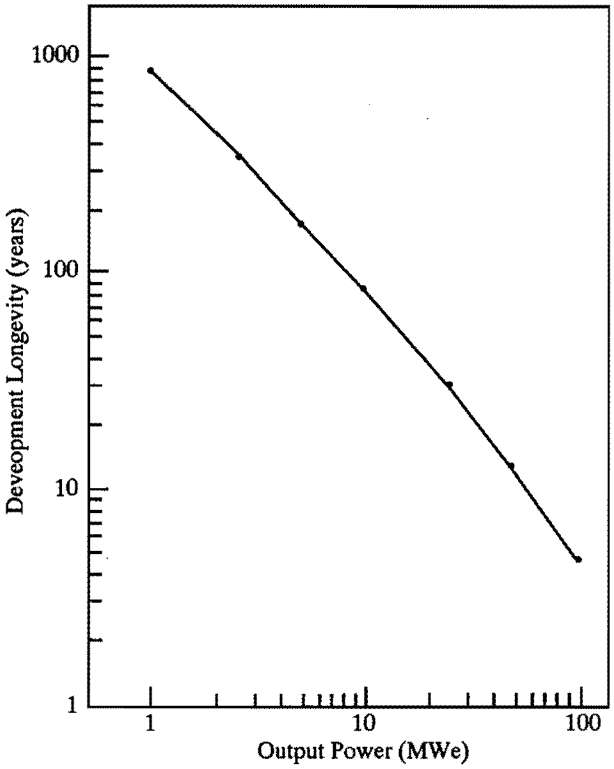

Figure 2. Development longevity as a function of output power for example given by Hanano et al. (1990).

Recovery of thermal energy from a hydrothermal system is sometimes compared with recovery of oil from a petroleum reservoir. However, there is an important difference: whereas some of the oil occurs in dead-end pores that cannot be accessed at all by wells, heat can not be similarly trapped in the rock. We can, in principal, recover all of the heat in a system at the surface if we are willing to wait for it to flow from the rocks into the reservoir fluid. The more efficient heat mining that results from lower production rates, as illustrated in the case above, results partly from this heat-flow effect. The important point from this example is that at high production rates only a fraction of the energy in a hydrothermal system might be recovered — the rest is left in the ground, perhaps to be mined later. Although the residual energy may not run the power plant used for initial reservoir exploitation, it may be useful for another application.

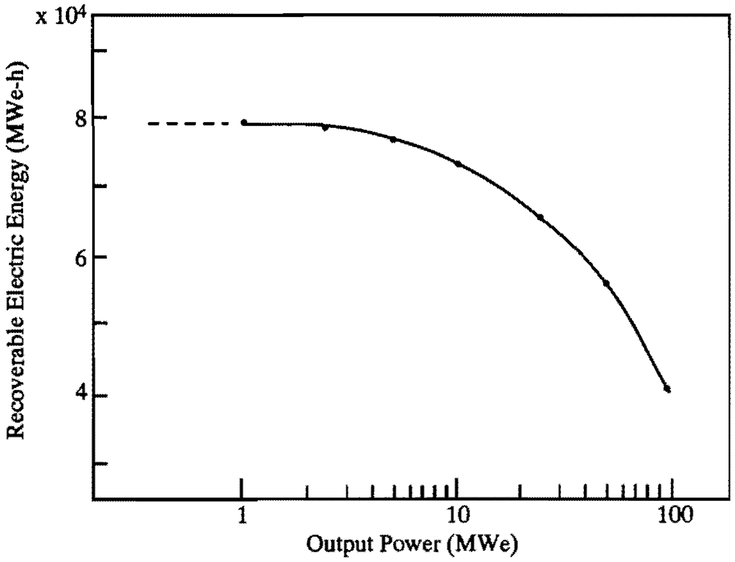

Figure 3. Total recoverable electric energy as a function of output power for example given by et al. (1990).

NEED FOR SUSTAINABILITY STUDIES

To the detriment of our industry, there is essentially no literature on the sustainability of production from geothermal resources. This leaves a void that is filled with conjecture and, sometimes, unfavorable assessments. Over-development and other reservoir problems have created questions in the minds of utilities, financial institutions, governments, and the public about the reliability of geothermal energy and its ability to contribute significantly to the world's energy needs over any significant time period.

There are several reasons for the lack of information on geothermal sustainability. Perhaps most importantly, the typical reservoir-performance study is carried out in a very conservative way, assuming a reservoir area limited to that known directly through drilling, and an arbitrary lifetime for the power plant, often 30 years. This is done to assure the financial backers that there is a low risk of project failure. Few studies have considered application of the heat remaining in the reservoir after the primary period of exploitation or the much larger store of heat lateral to and below the immediate reservoir. In addition, the high initial costs of geothermal development discourage acquiring a thorough knowledge of the resource during the feasibility study, financing, well-field installation, plant design, and construction phases of a project. Years of production may be required to gain an understanding of the total capacity and optimum heat-mining strategy for a particular hydrothermal system.

New studies are recommended to provide estimates of the sustainability of production from geothermal resources. These studies should account for: (1) the energy content of the whole thermal system, not just the immediate reservoir; (2) the expectation of improving technology, leading to greater ability to mine heat and turn it more efficiently into electrical power and other products; (3) the expectation that energy prices will rise in the future; (4) the value of geothermal energy for preserving the environment; (5) the value of geothermal resources due to their indigenous nature; (6) the value of geothermal energy projects in providing fuel diversity and risk diversity to a utility's or a country's energy portfolio; and, (7) the potential for mining heat from hot dry rock and deep crustal resources. The recommended studies should be undertaken with full consideration of changes being brought about by such institutions as the World Bank in their quest to develop new economic-analysis systems that account for measures to preserve the natural environment.

How can we determine the sustainability of production from geothermal resources? How can we better quantify the productive capacity of a hydrothermal reservoir at an early stage in a project and thereby avoid over-development? How can the geologists, engineers and financial people work together to match better the sustainable reservoir capacity to economic requirements? How can we incorporate the idea of sustainable development into assessments of geothermal resources? These are some of the questions for which we, the international geothermal community, need to provide answers.

IEA TASK V: SUSTAINABILITY OF GEOTHERMAL ENERGY UTILIZATION

The International Energy Agency is considering coordinating work to provide public information on the sustainability of production from geothermal reservoirs (Wright, 1996). The objective of this task is to study important facets of the production of energy from geothermal resources with the view of determining the long-term economic sustainability of such production.

This task is expected to fill a need for a worldwide resource assessment that is much more comprehensive than the usual geothermal resource assessment, and allow geothermal energy to be meaningfully compared with solar and wind energy as sustainable resources. It will help promote geothermal energy as a viable alternative, worthy of R&D for continued technology improvement.

Subtasks

The participants in this task (annex) shall share the coordinated work necessary to carry it out. The subtasks being considered for inclusion in this task are given below:

Subtask A: Ultimate Economic Production from Example Geothermal Fields

The participants will select certain geothermal fields throughout the world, representative of chosen geological classes of fields, for study. Selection criteria will include the availability of sufficient geological, geochemical, geophysical, drilling, well-testing, and reservoir-engineering data to characterize the fields well. An estimate will be made of the total thermal energy in the field including the known hydrothermal system and the additional heat contained in rocks around and beneath the system. A second estimate will be made of the total recoverable thermal energy in the field. Study participants will consider innovative methods for extracting the maximum amount of heat from these systems, and will account for expected improvements in technology, future energy costs, and other factors that affect project economics and ultimate energy production.

Subtask B: Sustainable Worldwide Geothermal Development Potential

Building upon the results of Subtask A, the participants will extend the analysis to the worldwide inventory of hydrothermal systems. An estimate will also be made of the worldwide potential for development of hot dry rock and deep geothermal resources. In this effort, the participants will coordinate and use the results of studies carried out under other Tasks, in particular Tasks III and IV. Expected improvements in technology, future energy costs, and other factors that affect project economics will be taken into account. The participants will develop one or more scenarios to indicate the potential for sustainable geothermal development worldwide, including both hydrothermal and HDR resources, over a time period measured in centuries.

Subtask C: Economics of Sustainable Development

The Participants will study the efforts being made by the World Bank, the United Nations, and other institutions to develop new methods of economic analysis designed to promote worldwide sustainable development of natural resources. They will evaluate the potential effects of these new economic methods on geothermal energy development worldwide.

Expected Results

The expected results of this task will include:

(a) Analytical reports estimating the ultimate economic energy production from example geothermal fields throughout the world, based on work under Subtask A described above.

(b) Analytical reports on the worldwide geothermal development potential and the level of production that can be sustained over some chosen period of time measured in centuries, based on work under Subtask B described above.

(c) Analytical reports on the effect on the sustainability of geothermal energy utilization of a potential worldwide shift to the economics of sustainable development, based on the work under Subtask C described above.

The reports shall be presented in special issues of international journals and at special sessions at international meetings.

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DISCLAIMER

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