THE SUSTAINABILITY OF PRODUCTION FROM GEOTHERMAL RESOURCES

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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.

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.

1. 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 over 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 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

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 (the Brundtland Commission) to mean development that "meets the needs of the present generation without compromising the needs of future generations" (Brundtland Commission, 1987). This is a different sense of the concept of sustainability than the strict sense presented in the paragraph above. 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.

Brown et al. (1990) offer a definition similar to that of the Brundtland Commission, namely that "a sustainable society is one that satisfies its needs without jeopardizing the prospects for future generations". However, these authors depart from the Brundtland Commission by stating that since geothermal energy is the only renewable that does not depend on sunlight, "it must be tapped slowly enough so as not to deplete the accessible reservoir of heat, and thus be truly renewable". This suggestion is not practical for the vast majority of hydrothermal reservoirs using today's methods of economic analysis and financial compensation.

McLeod (1995) quotes New Zealand's Resource Management Act in defining sustainable management as "managing the use, development, and protection of natural and physical resources in a way, or at a rate, which enables people and communities to provide for their

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social, economic, and cultural well-being and for their health and safety while; meeting the needs of future generations, safeguarding the environment, and avoiding, remedying, or mitigating any adverse effects of activities on the environment." This definition is operationally similar to that of the Brundtland Commission.

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 see that natural flows of thermal fluids persist for tens of thousands of years around cooling plutons, and that this natural flow recharges geothermal reservoirs. We will use the term "renewable" to indicate geothermal energy use at the rate of natural recharge. 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

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.

To the detriment of our industry, however, 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. Some see geothermal energy as just an interesting "flash in the pan", having no real future. For example, the United States General Accounting Office states that "evidence shows that most of the known large fields have already been developed and that operators are extracting energy from them faster than nature can replace it" (GAO, 1994). They use this argument to predict little future for geothermal power generation in the U.S. Problems with their conclusions include (1) ignoring the existence of undeveloped and undiscovered resources that could be brought into production to replace declines at producing reservoirs, and (2) neglecting the fact that although we are mining water from some geothermal systems, we may have removed little of the heat.

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.

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.

2. THERMAL ANOMALIES AND HYDROTHERMAL SYSTEMS IN THE EARTH'S CRUST

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. It is well known that Precambrian shields two billion years or more old typically contain vast areas of granitic plutonic rocks that bear intrusive relationships with the greenstones also common there. Base-metal and precious-metal deposits are intimately associated in time and space with intrusions that are dated from essentially every period of the earth's history. Igneous intrusion brings up enormous quantities of heat from depth and deposits it in the crust. Since such intrusions are believed to initiate hydrothermal convection systems, we will consider them briefly in this section.

Intrusion, Ore Deposition, and Geothermal Systems

There is little doubt that the larger, higher-temperature, and more vigorous geothermal systems are driven by igneous heat sources. No other known geologic process can cause the large thermal anomalies observed at the earth's surface in many areas of the world. In addition, most high-temperature geothermal systems display a spatial relationship to very young (<1 m. y. old) volcanic/plutonic events. White (1955, 1981), one of the first of many workers, documented evidence that certain classes of ore deposits are associated with hydrothermal activity of the kind seen in active geothermal systems. These deposits include disseminated-copper, epithermal-gold, base-metal replacement, and mercury accumulations. Specific analogies between hydrothermal systems associated with andesitic volcanoes and epithermal gold deposits were also drawn by Henley and Ellis (1983). Henley (1985) stated that "active high-temperature geothermal systems in volcanic-rock terranes are the archetypes of those systems responsible for epithermal precious- and base-metal ore deposits in analogous ancient terranes." In the Philippines, Mitchell and Leach (1991) supported such hypotheses and noted that "if the present total number of geothermal systems had remained more or less unchanged since the start of the late Miocene, and if each system were active for a million years, over 400 fossil systems would be expected, more than sufficient to have generated all the epithermal deposits and major prospects." Certain areas throughout the world are provinces of both hydrothermal mineral deposits and active geothermal systems. For example, a history of porphyry-copper and epithermal-gold mineralization extending over more than 100 million years has been observed in the Basin and Range province of the western United States (Titley and Hicks, 1966; Titley, 1982; Bagby and Berger, 1985).

We conclude that geologic processes similar, if not identical, to those occurring today in active geothermal systems have a persistent history in the geologic past. Known geothermal systems are not unique entities, but are just the present-day manifestation of geologic processes that have occurred throughout geologic time.

Many schematic models of the igneous-hydrothermal systems that result in ore deposits and geothermal reservoirs have been devised. They are quite complex if they include both the physical and chemical effects of the circulation of hot, highly saline fluids on the intrusion itself and on the host rocks. For our purposes, we will consider the simple conceptual model shown in Figure 1. Its salient features include an intrusive heat source at the base, which may be 2 to 10 km in depth to the top, with convecting hydrothermal fluids having streamlines that involve both the intrusion and the host rock. The temperature contours tend to bulge outward toward the top of the con-

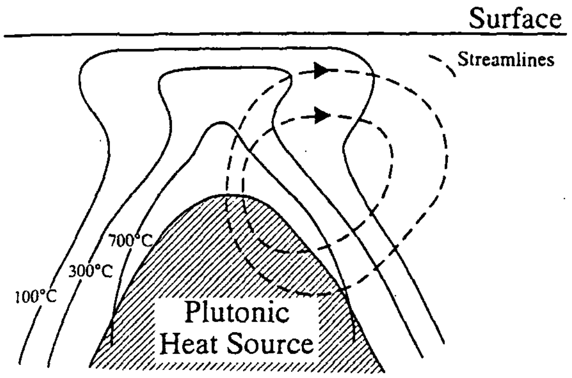

Figure 1. Simple, schematic model of a hydrothermal convection system with plutonic heat source.

vection system, creating the well-known mushroom-shaped thermal zone. Permeability variations and faulting may cause the actual shape of such a system to be quite asymmetric.

Numerical Simulation of Igneous-Hydrothermal Processes

Most models of hydrothermal systems in the geothermal literature refer to a hot region of some type at depth but only include details of the immediate, shallow reservoir itself. A few workers have attempted to describe the nature of the association and interaction between the igneous intrusion and the hydrothermal system (e.g., Elder, 1981). Consideration of how a pluton of limited volume may be expected to cool through conduction and ground-water convection provides useful insight into the relation between igneous intrusion, the formation of geothermal systems, and mineral deposition processes. Numerical model studies have been carried out by several investigators (Cathles, 1977, 1981; Norton, 1982). Cathles (1977) offered a series of two-dimensional computer models based on instantaneous intrusion of a pluton at 700°C into water-saturated, fractured host rock of uniform permeability and normal geothermal gradient. One of his modeled intrusions is 1.5 km wide, 2.25 km high, and is buried 2.75 km below the surface to the top. Figure 2 shows temperature contours for a uniform permeability of 0.25 md at times 1,000 and 5,000 years after intrusion. Features of note are the lateral spread of the thermal anomaly and its rise to the surface with time. Figure 3 shows the effect of permeability on cooling of the system. Steep cooling curves result from higher permeabilities due to vigorous convective transport of heat to the surface. Figure 4 shows the surface heat-flow anomaly as a function of time after intrusion. Notice that for purely conductive heat loss (zero permeability), a clearly anomalous heat-flow expression never reaches the surface. As the permeability increases beyond 0.05 md, maximum surface heat flow increases greatly.

Such studies as this and others allow their authors to draw 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; (3) for purely conductive cooling, the pluton never produces a significant surface heat-flow anomaly; (4) increasing the width of the pluton results in concentration of convection over the edge of the intrusion rather than over the center, and the zone of maximum fluid circulation may lie outside of the intrusion altogether; and, (5) enormous volumes of water circulate through the system, with the most vigorous fluid convection taking place prior to arrival of the thermal anomaly at the surface. These conclusions have important implications for geothermal exploration which, unfortunately, we will not have space to discuss in this paper.

Duration of Thermal Anomalies

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 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."

While all of these results are interesting and pertinent to geothermal-energy utilization, 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, as we shall see, exploitation that exceeds natural recharge can greatly shorten the system lifetime.

Natural Recharge of Hydrothermal Reservoirs

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 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. However, surface heat-loss estimates may not be reliable for at least three reasons: (1) a complete enough heat-flow survey must be performed to incorporate the extreme edges of the anomaly, including any zones of lateral hot-water flow, which may be extensive; (2) groundwater movement or other hydrologic disturbances may render shallow heat-flow determinations unreliable; and, (3) an accurate inventory of heat lost from hot springs and other features is difficult to make. 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 260°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. Yearsley (1994) observed that at the current production rate of 25 MWe, there has been no temperature decline, and 90% of the 500 psi pressure decline took place in the first four years of production.

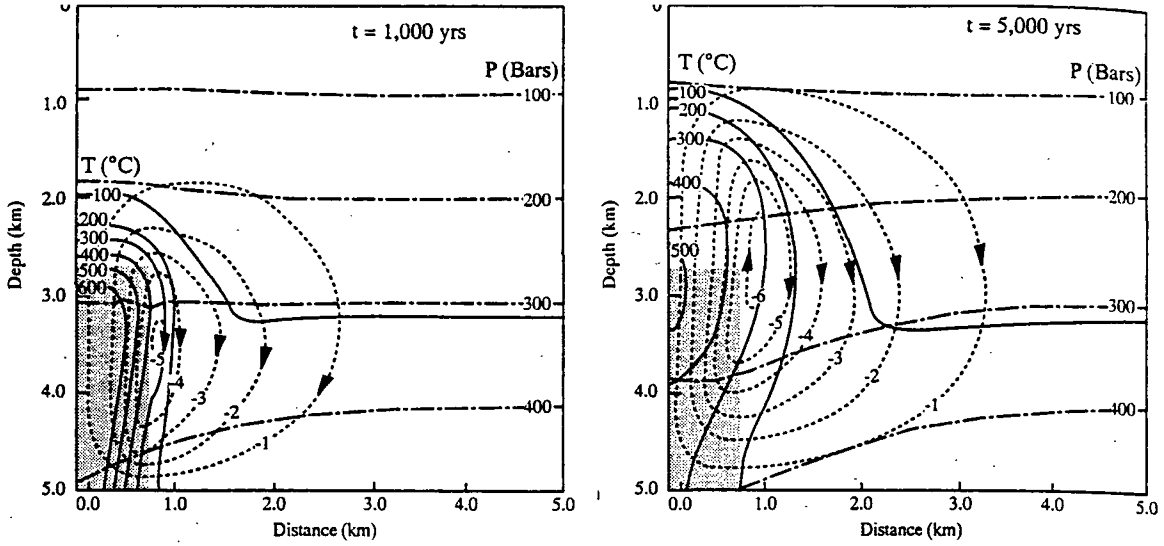

Figure 2. Evolution of a hypothetical hydrothermal system with time after intrusion of 700°C pluton. Two-dimensional model, with intrusion shaded. Permeability is 0.25 md (after Cathles, 1977).

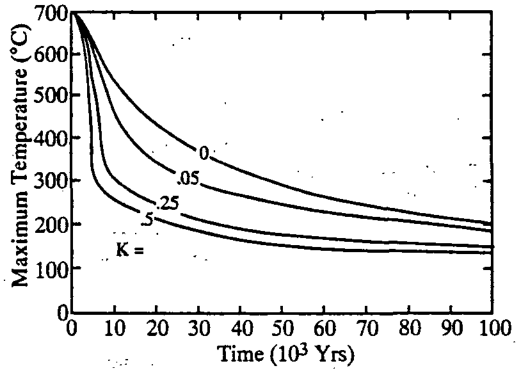

Figure 3. The effect of permeability (K, md) on the cooling rate of the plutonic-hydrothermal system shown in Figure 2 (after Cathles, 1977).

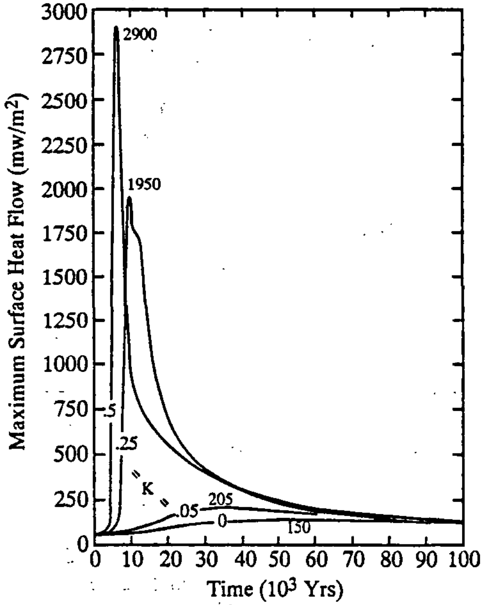

Figure 4. Maximum surface heat-flow anomaly with time at various values of permeability for the plutonic-hydrothermal system shown in Figure 2 (after Cathles, 1977).

Other estimates of natural recharge rates and very 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. Reservoir modeling of the natural state of the geothermal field at Miravalles, Costa Rica, was carried out by Haukwa et al. (1992). They concluded that the rate of natural recharge is 130 kg/s at a temperature of 260°C, for a thermal input of about 150 MWt. Their modeling indicated that the field can support 55 MWe of generation for 30 years with or without injection, but maintaining 110 MWe for 30 years is problematic due to potential problems with thermal breakthrough or scaling of the formation due to boiling. The authors emphasized that the limits and permeability distribution of the field are incompletely known, and that this lack of knowledge could markedly affect their results.

The small field at Krafla-Hvitholar was modeled by Tulinius and Sigurosson (1989), who estimated the natural recharge to be 10 kg/s of fluid at 300°C (13 MWt). Pritchett et al. (1991) reported the results of a natural-state simulation of the Sumikawa reservoir, Honshu, Japan. Recharge to the system was estimated at 31 MWt, comprised of 25 MWt from fluid inflow and 6 MWt from conduction. The system was predicted to be capable of sustaining 50 MWe of generation for more than 50 years. The large volume of the reservoir, about 40 km^3, contributes to the long life despite the low recharge rate. 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 355°C fluid from depth.

I performed a rough integration of the heat-flow maps given by Walters and Combs (1992) and Thomas (1986) for The Geysers region in California. Graphically integrating Thomas' map within the 250 mW/m^2 contour, which includes and is somewhat larger than the current production zone, yields an area of about 200 km^2 having a conductive heat loss of about 80 MWt. The production area sits at the southwest end of a much larger heat-flow anomaly of about 750 km^2 within the 4 heat-flow unit (168 mW/m^2) contour. The conductive heat loss from this larger region is roughly 170 MWt. These figures are surprising low in view of the enormous thermal resource at the known Geysers field. If the field is assumed to encompass a block of rock 100 km^2 in extent and 3 km thick, the heat content above 15°C is roughly 1.7 X 10^{20} J, or 170 Quads (Q), equivalent to burning 28 billion barrels of oil or 6.2 billion short tons of coal. For comparison, the total energy consumption in the United States for all uses is about 80 Q/y.

In summary, it appears 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 10^{16} to 10^{17} J. 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.

3. ENERGY PRODUCTION FROM HYDROTHERMAL SYSTEMS

By convention inherited from the utility industry, the feasibility of geothermal projects is generally evaluated in terms of their ability to repay the investment during an arbitrary lifetime, usually 30 years. The rate of energy extraction is determined primarily by the number of production wells needed to supply the power plant, and can be made very much larger than the natural resupply rate. In the early stages of a project, it may not be possible to estimate the natural resupply with any reliability. In any case, the production rate is rarely limited to the natural resupply rate because to do so would result in a project so small as to be uneconomic.

Liquid-Dominated Hydrothermal Systems

Elder (1981) gives a simple, informative treatment of the exploitation of liquid-dominated hydrothermal systems resulting in estimates of their expected lifetimes. He uses the term "heat mining" to refer to that interval during which the particular hydrothermal system has matter and energy extracted artificially at rates considerably greater than in the natural, undisturbed system.[1] He provides estimates of the net efficiency of conversion of reservoir heat to electrical power that range from 5% for an atmospheric-discharge turbine to 15% when ample cooling water is available for the condenser. He illustrates simple exploitation of a system with a large thermal volume and bores sufficiently deep, and with sufficiently small discharge, so that no flashing occurs in the ground or uncased sections of the bores. Figure 5 shows schematically the expected behavior that, after a certain period of time, temperature, pressure, and power output will stabilize at values which may characterize the production for a long period of time. Elder (1981) then shows results for a constant-power strategy as illustrated in Figure 6. In his example, the natural power input to the system is 500 MWt, and electrical power productions of (a) 100 MWe, (b) 150 MWe, and (c) 200 MWe are shown. Using a 10% conversion efficiency, these three cases correspond to extraction of 1,000 MWt, 1,500 MWt, and 2,000 MWt of power from the system, respectively. Power generation continues at a constant level through addition of new wells as temperature and pressure drop until an abandonment condition is reached. In this example, if the ratio of rate of energy removal to rate of resupply is 2:1 (Figure 6a), effects are minor and the system can be utilized for a long period of time, depending on the reservoir volume. However, as the power extraction goes up and this ratio increases to 4:1 (Figure 6c), the effects are dramatic, and severely limit the duration over which the reservoir can be used in this mode.

Hanano et al. (1990) also give a helpful discussion of reservoir longevity for liquid-dominated systems. They use a simulation technique comprised of a reservoir model, a well-flow model, and a system-management model to study reservoir pressure and temperature behavior in various development cases. The management model couples the reservoir and well-flow models to evaluate field decline, longevity, and recoverable electric energy. 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. 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.

Figure 7 shows the simple reservoir model used in an illustrative example given by Hanano et al. (1990). All production comes from the production block, and the separated water is all injected into the injection block. Boundary conditions are constant temperature and pressure. Figure 8 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 increased to maintain a specified output. As the production rate is increased, pressure declines further. The steam production rate of a typical well as a function of output power is shown in Figure 9, demonstrating the profound effect of output power on well decline. Figure 10 shows the field longevity until abandonment as a function of output power, and Figure 11 shows the recoverable electric energy over the system lifetime as a function of output power. Total recoverable electric energy

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[1] This use of the term "heat mining" predates and seems preferable to the more recent use by some to refer to exploitation of hot dry rock systems.

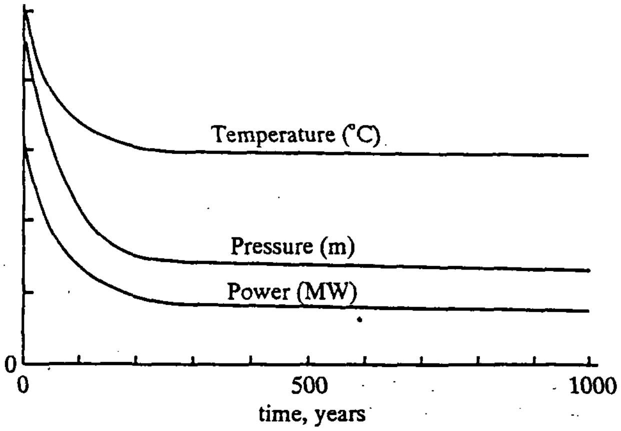

Figure 5. Schematic illustration of expected temperature, pressure, and power-output behavior of hydrothermal system under production.

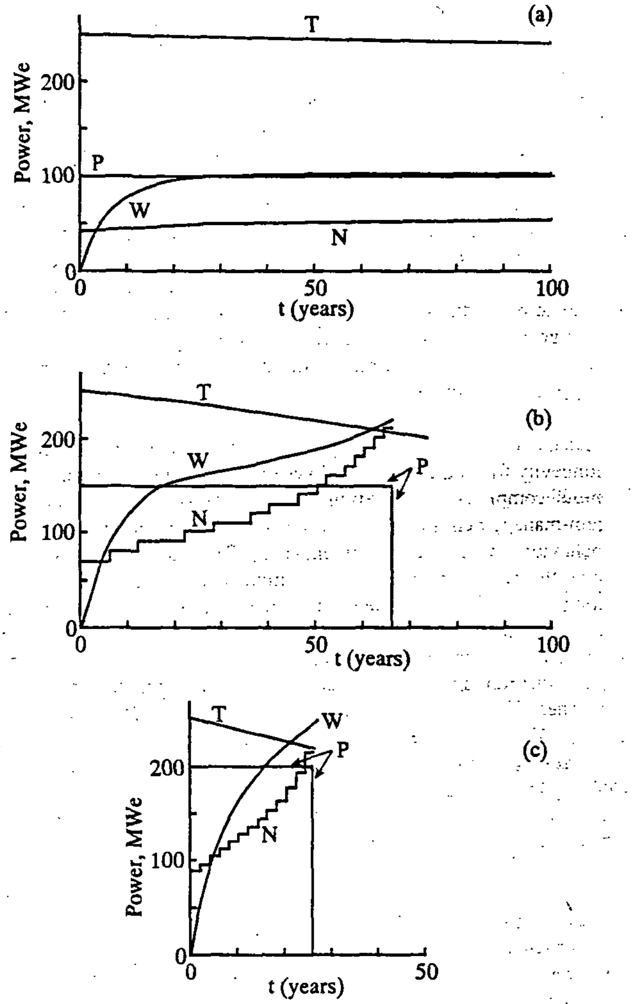

Figure 6. Constant power generation at (a) 100 MWe, (b) 150 MWe, and (c) 200 MWe for a hypothetical hydrothermal system whose recharge rate is 500 MWt with 10% overall conversion efficiency. T = temperature, W = pressure loss, P = power generated, and N = number of wells required. (b) and (c) show the end of power generation when abandonment conditions are reached (after Elder, 1981).

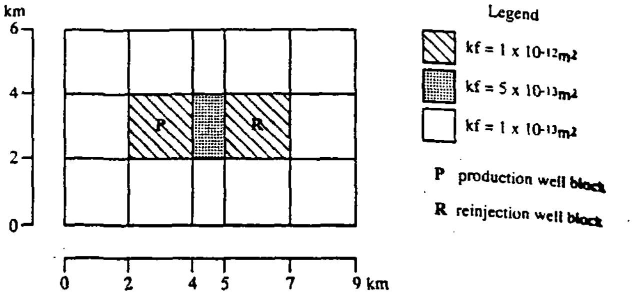

Figure 7. Simple reservoir model used by Hanano et al. (1990).

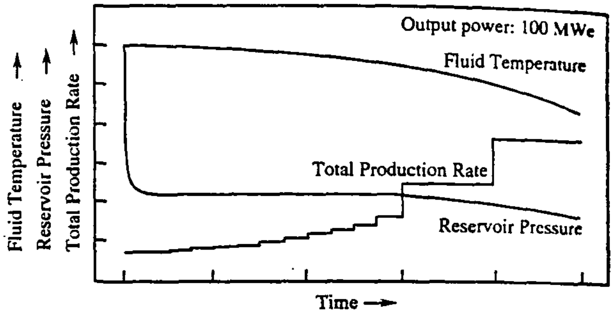

Figure 8. Temperature and pressure behavior of the reservoir, and increasing production rate needed to meet 100 MWe constant power output (after Hanano et al., 1990).

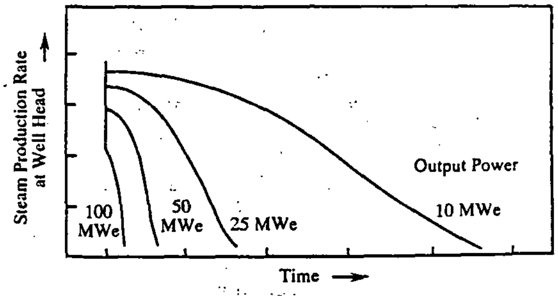

Figure 9. Steam production rate per well as a function of output power (after Hanano et al., 1990).

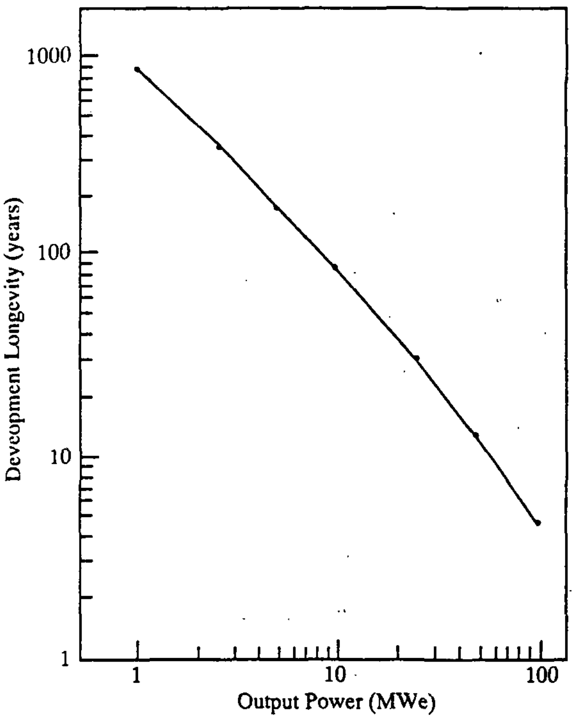

Figure 10. Development longevity as a function of output power for example given by Hanano et al. (1990).

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.

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.

Vapor-Dominated Hydrothermal Systems

Vapor-dominated systems form in response to the interplay between restricted recharge and limited surface discharge (White et al., 1971). With both present, an existing liquid-dominated system may boil down, leaving steam as the pressure-controlling medium in the fractures and pores. With little or no recharge, the system is fluid-limited and can become depleted with discharge of steam through production wells, leaving the vast majority of heat remaining in the rock. For example, in a liquid-dominated hydrothermal system with 15% porosity, about 80% of the heat resides in the rock and about 20% resides in the water. In a vapor-dominated system having the same porosity, 99% of the heat resides in the rock and only 1% resides in the steam. The problem in vapor-dominated systems is how to mine this thermal reservoir in the absence of large amounts of water furnished by nature. We will briefly outline activities at Larderello, The Geysers, and Matsukawa to extend the life of these important resources.

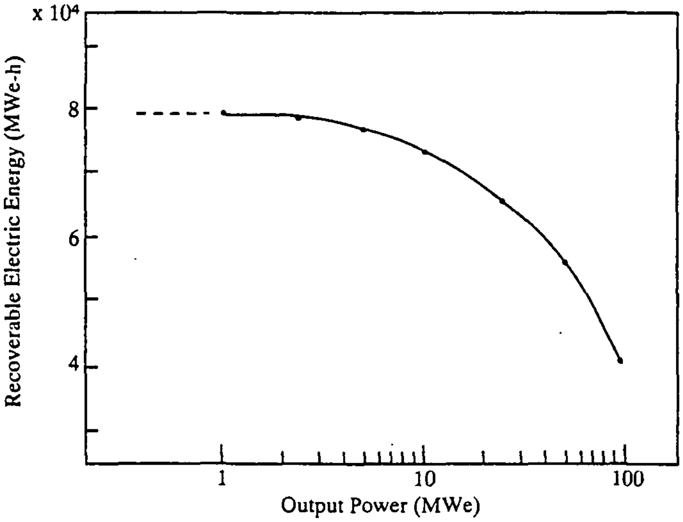

Figure 11. Total recoverable electric energy as a function of output power for example given by Hanano et al. (1990).

Two successful strategies for sustaining production at Larderello, Italy, were outlined by Cappetti and Stefani (1994) — deep drilling and injection. Deep drilling has shown that highly permeable layers are separated by layers having low permeability, impeding the vertical migration of steam from depth. In the south-central part of Larderello, drilling to depths of 1,500 - 2,500 m discovered high productivity and increased reservoir pressures, making it possible to increase production from the area and to offset the decline of the wells already in production. Additionally, injection experiments in the field have given positive results and indicate strategies that may be applicable elsewhere. Injection at the top of the reservoir in areas where fractures allow downward percolation has been highly successful, whereas deep injection has not yielded positive results. After 15 years of injection at the rate of 80 l/s into the Valle Secolo area, it was found that (1) 80% of the injected water was vaporized, (2) noncondensible gas (NCG) content declined, leading to greater powerplant efficiency, (3) an increase in reservoir pressure of about 0.2 MPa was observed, and (4) there was no decline in temperature. Cappetti and Stefani (1994) concluded that it is necessary to inject into zones where the wells produced considerable amounts of fluid in the initial phase of development, and to inject at the top of the reservoir using wells that had previously been good producers.

At The Geysers field, increased steam pressure decline coincided with the rapid development of new power production between 1982 and 1989 (Barker et al., 1992). Sustained field development started in 1972, with an average of 67 MWe/y installed through 1981. From 1982 to 1989, the average rate of development was 150 MWe/y. Beginning in 1985, a roughly 30%/y decline in pressure was noticed, whereas the previous decline rate had been about 6%/y.

Injection experiments have been performed with mixed results in several parts of The Geysers field. In some cases, injection has not increased available steam or has produced highly corrosive steam containing hydrochloric acid. Currently, a three-year experiment is being undertaken in the southeast portion of the field by Unocal, Calpine, Northern California Power Agency, Pacific Gas & Electric, and the U. S. Department of Energy (Voge et al., 1994). Injection into one well at rates of 400 to 800 gpm (25 to 50 l/s) has resulted in increased steam production in some nearby areas. Within several days of the 6 January 1994 start of injection, enhanced steam production totalling 45 thousand pounds per hour (kph) (5.7 kg/s) was seen from the five producing wells on the injection well pad. Other wells in the area being monitored also showed production increases as the injection test progressed, although some wells showed decreases. Over the first four months of the experiment, the average injection rate was 606 gpm (38.4 l/s), and 40.7% by mass of this amount was recovered as produced steam from the study wells. Since the time from the beginning of injection to the reporting of these results was only about six months, the fraction of injection-derived steam is expected to grow as time passes.

The results of this experiment are important to a planned project to bring waste sewage water into the southeast portion of The Geysers field. A 26-mile (42-km), 24-inch (61-cm) diameter pipeline would carry as much as seven million gallons per day (300 l/s) of treated municipal waste water from Lake County, California, which lies east of the field. The pipeline is expected to cost about USD 40 million, to require about $6 million in expenditures for secondary distribution and injection facilities, and to further require about $2 million in annual operating costs. Increased production of 50 to 100 MWe is anticipated. If this injection project is successful, an even larger project has been mentioned to bring waste water into the central part of The Geysers field from cities such as Santa Rosa which lie to the west.

Generation of electrical power has continued since 1966 at the Matsukawa field in Japan. Full power output of 22 MWe has been sustained, although reservoir pressure is declining and some wells are displaying an increasing amount of superheat, a signature of the consumption of water in the reservoir (Hanano et al., 1991). These effects are most notable in the northern portions of the reservoir, since the limited recharge is from the southwest, where reservoir pressure and steam production have declined least. To sustain steam production and to extract the remaining heat energy in the reservoir, injection of steam condensate into one well was begun in 1988 (Hanano et al., 1991). Injection of 20 t/h (5.6 kg/s) into well MR1 resulted in increased production in well M5 of 10 t/h of steam, a 67% increase, and 10 t/h of liquid at 150°C. The time interval between start of injection and increased steam production was 50 days despite that fact that the two wells are only 300 m apart. Essentially all of the injected water is recovered as either steam or liquid from the production well. Since the heat energy of the injected fluid relative to 0°C is 0.5 MWt, and the increased production is equivalent to 9.4 MWt, the heat recovery is 8.9 MWt. And since the vertical heat flux over the Matsukawa reservoir is about 1,500 mW/m^2, the heat flux extracted by the injection experiment is about 200 times the natural flux, giving an indication of the efficiency of this heat mining experiment.

4. ECONOMICS AND SUSTAINABLE DEVELOPMENT

Natural resources may be divided broadly into renewable and nonrenewable categories. Nonrenewable resources, as the name implies, are finite, so that using them at all depletes the stock. The national and international issue with them is the rate at which the stock should be depleted over time. Renewable resources are capable of regeneration. Use of them by extracting their sustainable yield allows the resource to renew itself. The national and international issue with renewable resources is the rate at which they should be used so that their stocks are maintained. We have seen that geothermal resources are renewable at some generally small level of production, but that production can take place at a higher level for a certain period of time. Geothermal resources, then, are on a boundary between being renewable and nonrenewable.

Traditional and Sustainable Economics

In 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 developer to extract energy from a geothermal resource in a sustainable way.

Traditional methods of 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. Growing demand could be met simply by increasing production. We are rapidly approaching a time when this will no longer be the case. In the future, we will be constrained to more innovative methods of meeting demand which do not destroy the earth's natural systems. The discount rate traditionally applied in economic analyses is the current opportunity cost of capital, generally in the range 9% to 12%. For long-term decisions, it is argued that smaller discount rates should be used, since we cannot be sure that positive rates of return on investment will persist, especially if the natural resource base deteriorates (Serageldin and Steer, 1994). Smaller discount rates would lead to higher present value of the future asset, and perhaps change the way we go about development. However, there is agreement neither on what the discount rate should be nor on whether manipulating it would be an appropriate intervention.

The World Bank is one institution working to evolve and implement an operational concept of sustainable development. They recognize three viewpoints that must be integrated, those of the economist, those of the ecologist and those of the sociologist (Serageldin and Steer, 1994). Traditional economic analysis sees these three viewpoints as encompassing primarily the elements shown in Figure 12. A sustainable-development analysis would see the same three viewpoints as encompassing an expanded list of elements shown in Figure 13, many of which are difficult to value monetarily. A sustainability approach to economic analysis would stress (1) the importance of valuing environmental assets and their services, (2) the need to ensure that investments truly build up the stock of man-made capital, and (3) the need to think about safe minimum standards when environmental capital is critical (Pearce and Warford, 1993).

On a national level, there is growing recognition that the traditional measures of income such as gross national product (GNP) do not reflect a country's true economic situation because they ignore natural-resource depletion and degradation (El Serafy and Lutz, 1989). The fact that these issues are not properly dealt with even under the current United Nations System of National Accounts (SNA) is a seri-

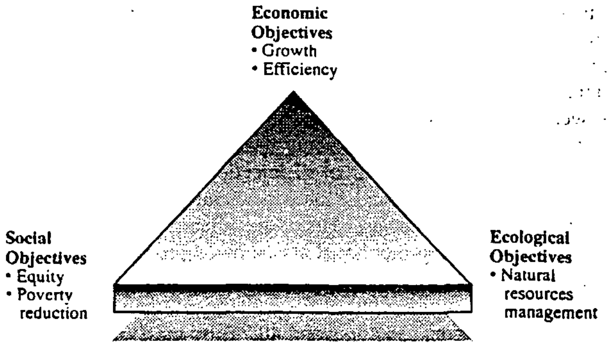

Figure 12. Elements in a traditional project economic analysis (after Serageldin and Steer, 1994).

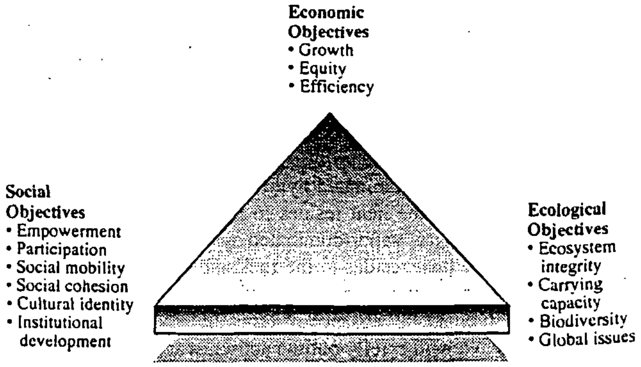

Figure 13. Elements in a sustainable-development project economic analysis (after Serageldin and Steer, 1994).

ous flaw. For example, the costs of actions taken to protect the environment are accounted for as income instead of being deducted from the national account. In addition, the loss of natural resources such as soil or minerals entails no charge to the national account to reflect the decrease in future production. Policy decisions based on such faulty measures are themselves often faulty. A development path is sustainable if and only if the total stock of overall capital assets remains constant or rises over time. Capital assets include manufactured capital (infrastructure), human capital (knowledge, skills), and natural or environmental capital (forests, soil, energy resources). The proper measure of national income corresponding to sustainability is equal to the amount that can be consumed without running the stock of capital down (Pearce and Warford, 1993). It is apparent that new national accounting methods must be devised if the true value of the natural environment and its resources is to be reflected. Without a revised accounting system, the wrong market signals will continue to be sent to policy makers, and we will continue on a downward-spiraling path of natural resource degradation.

Pearce and Warford (1993) have introduced the concept of total economic value (TEV) as a way of bringing environmental 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 analyses if these analyses include external costs of using the resource. Indirect-use values consist mainly of values given by ecologists (see Figure 13), 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 before modified systems of national accounts and project analysis will be adopted that take the natural environment into full consideration.

Sustainable Economics and Geothermal Resources

Although satisfactory techniques for making economic analyses of sustainable development do not yet exist, we can be sure that they are coming. When these techniques are available, they will help in devising and implementing regional, national and international development plans that may be quite different from those in use today. Until that time, we can still use some of the principles discussed above to help us consider the sustainability of production from geothermal resources from today's perspective.

The traditional geothermal project analysis fails to capture a true measure of the useful energy that can be produced from a geothermal resource. Yet, this type of analysis is the only thing available in the literature for others to use. The impression left by such incomplete analyses is that the resource will be depleted far sooner than in fact it actually will be. Field production is usually simulated in feasibility studies and carried out in practice in such a way that pressure and temperature are allowed to decline at a certain acceptable rate to the project time limit or to an abandonment criterion. The field is said to be depleted when it will no longer sustain some chosen level of generation. At this point, however, significant quantities of heat may remain in the rock-fluid reservoir system. A residual value for the geothermal resource after initial exploitation is not usually recognized since its present value would be only a few percent of the project cost using traditional economic analysis. Strategies to capture and use remaining heat for further power generation or for direct uses are rarely explored.

I believe that it is important for the world geothermal community to undertake meaningful studies of the sustainability of geothermal production that go far beyond the usual reservoir study. Sustainability studies would be useful in providing information to policy makers and in guiding us in our own endeavors. Some of the elements that should be included in such sustainability studies are discussed below. Each element must ultimately be stated in economic terms, since either traditional or sustainable economics will continue to drive or limit geothermal power production.

Total Energy in the Resource

As we have discussed, the amount of heat remaining in reservoir rocks after the primary period of exploitation may be large. However, residual heat within the known reservoir itself is only a small part of that available in the whole thermal anomaly. Rocks lateral to and beneath the reservoir contain significant quantities of heat. Little may be known about the true boundaries of the thermal system, especially the lower boundary. Methods which address the mining of heat from the total system are just now being conceptualized. Takahashi and Hashida (1992) have written about a project in Japan to develop methods of mining heat lateral to a hydrothermal reservoir. In their so-called "hot wet rock" reservoir design, the size of the hydrothermal system would be enlarged by fracturing adjacent rocks and connecting them to the natural hydrothermal system. This idea has significant merit, and its technical and economic feasibility need to be closely examined.

Methods to mine deep heat in geothermal systems also need to be conceptualized so that they can be evaluated and demonstrated. The Larderello reservoir has been successfully extended downward through deep drilling (Cappetti and Stefani, 1994), but the amount of energy in the roots of this large thermal resource is still unknown. Deep drilling is also being undertaken elsewhere. A project of Japan's New Energy Development Organization (NEDO) known as the "Deep-Seated Geothermal Resources Survey" is working to define directions for the development of deep geothermal resources, reduce the risk of deep resource exploration, and put deep geothermal energy into practical use (Yagi et al., 1994). A 4,000 m hole is being drilled in the Kakkonda geothermal field as part of this project.

In many instances, we know that the thermal system is much larger than the reservoir under production or being explored. For example, Laky et al. (1989) state that manifestations of the Ahuachapan-Chipilapa geothermal system in El Salvador spread over 100 km^2, and that the well-studied Ahuachapan reservoir is only part of this thermal system, which extends to the east and southeast. Recharge to Ahuachapan-Chipilapa occurs at the estimated rate of 225 kg/s of 250°C fluids, yielding a thermal flowthough of about 250 MWt (Aunzo et al., 1989). This recharge is believed to represent the outflow of a much larger, completely unexplored hydrothermal system under the Laguna Verde volcano. There are examples like this of only partly explored geothermal systems in virtually every geothermal province. Our studies of geothermal sustainability should include estimates of the energy in the entire thermal system, even to the point of reasonable conjecture about the lateral and lower boundaries of the system. In this way, we will reach a much more plausible assessment of geothermal sustainability than is now available from current reservoir studies.

Improved Technology

Any evaluation of the sustainability of production from geothermal resources must consider that the technology will continue to improve. Modern geothermal power plants are at least 25% more efficient in their conversion of steam to electricity than they were two or three decades ago. The first plants at The Geysers field in 1960 had a steam conversion rate of about 20 lbs (9.1 kg) of steam consumed for each kilowatt-hour of power generated. The much more modern plants brought on line in the mid-1980s have conversion rates of 14.5 - 15 lbs/kwh (6.6-6.8 kg/kwh). Drilling technology has also improved, resulting in lower costs and less financial impact on development from these expensive operations. The development of better reservoir simulation models and effective chemical tracers enables us to do a better job of designing production and injection strategies that optimize use of the resource. Petty et al. (1991) have shown that the amount of geothermal power available in the United States at costs of $0.1/kwh or lower should increase by 27% with reasonably expected improvements in technology. Their estimate does not account for any increased ability to mine heat from the lateral and deep margins of geothermal systems resulting from better technology.

The important point is that the geothermal industry is young and is still going steeply up the learning curve in geothermal technology. There remain many opportunities for further improvement in this technology. As a result of successful R&D programs, we can expect that the cost of generating geothermal power will continue to decline, the amount of useful energy that can be economically extracted from each reservoir will increase, and the quantity of geothermal reserves as a percentage of the total resource base will grow.

Energy Costs

Energy costs today are low in most parts of the world. In the United States, low natural gas prices have so undercut geothermal energy prices that the market for new geothermal generation is now virtually nil. However, the growth in energy consumption is faster than the growth in population in developing countries, and as demand outruns supply, costs will increase. Predicting future costs of energy has always proven to be difficult. Nevertheless, competing energy costs greatly affect the amount of geothermal energy that can be economically developed. Studies of the sustainability of geothermal energy production must be based on assumed competing energy costs, and reasonable projections will be needed for such studies.

Environmental Benefits

With increasing awareness of the need for sustainable management of natural resources, and with development of new methods of making sustainable analyses, the value of clean energy sources such as geothermal energy will rise. This will happen very dramatically if global warming proves to be a significant problem. There have been highly criticized attempts in the United States to assign a cost to the environmental damage caused by energy extraction and use (Hubbard, 1991) and to have external environmental costs included in market decisions (Ottinger et al., 1991). For example, the State of Nevada has determined that 1.5 cents/kwh should be added to coal-fired generation costs because of their atmospheric emissions to get a valid comparison with geothermal generation costs. Our estimates of the sustainability of production from geothermal resources should account for expected increases in compensation for the environmental benefits of geothermal energy.

Value of Indigenous Resources

There is value to any country that has geothermal resources in the fact that they are indigenous resources, not subject to uncertainty of supply and not requiring hard currency for purchase. This additional value can be estimated for many countries today, and its growing importance, especially to countries poor in other energy fuels, should be recognized in studies of geothermal sustainability.

Value of Fuel Diversity

There is value in having a reliable alternate source of energy available. Countries that rely heavily on hydropower, for example, depend on rains to fill their reservoirs and streams — rains that may or may not come. Recent droughts in Central America have left many countries there without adequate generation capacity. Geothermal power generation is far more reliable than hydropower in this regard. The additional value of geothermal resources due to fuel diversity can be roughly estimated for many countries, and should be recognized in geothermal sustainability studies.

Value of Risk Diversity

There is value to a utility or a country in having projects with diverse risk profiles. Geothermal projects have relatively greater initial risks while the reservoir is being proven and the power plant optimized. However, the long-term risks for such factors as escalating fuel price are lower for geothermal energy than they are for fossil or nuclear energy sources. Fossil-fuel power generation costs can be expected to escalate at the general inflation rate, but geothermal costs will escalate at perhaps only one-third of the inflation rate. This factor should be accounted for in our studies of geothermal sustainability.

Sustainable Overall Energy Supply

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 evaluate the role of hot rock and deep-crustal resources. Hot rock resources occur in two geologic environments, (1) at shallow, currently drillable, depths in the near vicinity of recent (< 1 m.y. old) plutonic and volcanic activity, and (2) at depths of 5 to 15 km everywhere on the earth. The magnitude of the resource base is not well quantified, but is known to be very large. Smith and Shaw (1979) estimate that the amount of thermal energy in igneous-related geologic environments between the surface and a depth of 10 km in the United States is about 10^{24} J. If only 1% of this energy could be produced, it would furnish about 30 million megawatt-years of electrical power at a thermal conversion efficiency of 10%. Diment et al. (1975) state that the heat content of the crust above surface temperature to a depth of 10 km in the United States is 3×10^{25} J, 30 times more than in igneous systems. This latter resource is huge compared with the demand for energy in the U.S., which totals about 8×10^{19} J/y for all uses. If technology could be developed to use hot-rock and crustal-heat resources, they could make a very significant contribution to our needs. In terms of sustainable geothermal development, our proposed studies need to examine closely the likelihood that such resources will become economically viable and what their contribution could be. The important hot dry rock studies in the United States, Western Europe, Japan, and Australia can be used as a starting point.

5. CONCLUSIONS AND RECOMMENDATIONS

Current assessments of geothermal reservoirs do not give an accurate picture of their long-term production potential. Absent a literature on the sustainability of production from geothermal resources, people who lack an understanding of our industry make inaccurate evaluations of our potential. International funding institutions, governments and environmental advocacy groups have concerns about the reliability and potential of geothermal energy, and lack the conviction to support us aggressively. We, the geothermal community, have done a rather poor job of assessing our own potential and have failed to communicate effectively about the promise of our industry. We must take steps to correct these deficiencies.

I recommend that new studies, based partly on the ideas presented above, be undertaken to provide a meaningful evaluation of the expected contribution geothermal energy can make to society, both in the short term and the long term. An international geothermal sustainability studies group, comprised of geologists, reservoir engineers, power-plant engineers, economists, environmentalists and others, is needed. I am interested in helping put together such a study group to carry out the recommended studies, and would welcome participants who come forward.

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7. DISCLAIMER

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