CHAPTER 3

Recoverable EGS Resource Estimates

3.1 Scope and Approach

This chapter provides a rationale and methodology for estimating the amount of useful energy that could be recovered from Enhanced Geothermal Systems (EGS) over the range of accessible depths and temperatures that exist in the United States. As discussed in Chapter 2, the EGS resource base is defined as the total thermal energy in place in the Earth's crust to the depth that we can reach with current technology. Thus, the estimated resource base for EGS presented in Chapter 2 is a measure of the total contained energy. Here, we want to estimate what fraction of this amount is recoverable.

If we limit our calculation of stored thermal energy in place to a depth of 10 km beneath the land area of the United States, then the amount of thermal energy in the crust is so large (about 14 million quads) that we can view it as sustainable (see Chapter 2, Table A.2.1). Even if we were to use it to provide all the primary energy consumed in the United States, we still would be depleting only a tiny fraction of it.

The depletion aspect requires additional exploration and detail. Geothermal is often classified as a renewable resource, but the time scale for its renewablilty is certainly longer than for solar, wind, or biomass energy, which have daily and annual cycles. For instance, a fractured EGS reservoir is cooled significantly during heat-mining operations over its normal project life of about 20 to 30 years, as a result of heat-mining operations. If the reservoir was abandoned at that point, the rock would recover to its initial temperature in 100 years or less (Armstead and Tester, 1987; and Elsworth, 1989 and 1990). With the time for full recovery of a former active reservoir approaching a century, one might not categorize geothermal heat mining as a sustainable energy resource. However, as long as the fraction of stored heat that is being mined in any year is a small fraction (<10%) of the total assessable resource base, geothermal can be treated as fully renewable and, therefore, a sustainable resource. Given that the U.S. geothermal resource base is about 14 million EJ, we would always be utilizing much less than 10% annually of the total thermal energy, even if all of our primary energy came from geothermal resources.

Chapter 2 characterized the EGS resource primarily by depth and temperature. In some regions, the EGS resource is available at high temperatures at shallow depths making energy recovery easier and less costly than other lower-grade regions, where deeper drilling is needed to reach useful rock temperatures. Another positive attribute of EGS for the long term will be the ability to locate heat-mining operations near end users. For example, an EGS site being developed in Switzerland is within the city limits of Basel. However, a significant portion of the resource will be inaccessible from the surface, due to its location under state and national parks, wilderness, military sites, or very high elevations. In addition, developed areas will not be suitable for EGS development, including major roads and utility corridors, airports, urban areas, and others. As it turns out, these inaccessible areas amount to only a small fraction of the total, leaving a significant amount of the stored thermal energy contained in accessible regions available for capture and utilization on the surface.

As discussed in Chapter 7, there are several factors that control the amount of the resource that can be recovered as heat or converted into electricity. These include the initial rock temperature and the maximum temperature drop that can be tolerated by the heat/power plant (i.e., the reservoir abandonment temperature), the volume of rock that can be accessed and stimulated, the active or effective heat-exchange area (controlled by the length, width, and spacing of the existing and stimulated fractures), and the flow rate of the water through the connected fractures (controlled by the permeability and the pattern of the injectors and producers) (Armstead and Tester, 1987; Ellsworth, 1989; and Sanyal and Butler, 2005).

Recoverable thermal energy was estimated, assuming an abandonment temperature 10°C below the average initial rock temperature in the reservoir. Numerical modeling studies by Sanyal and Butler (2005) have indicated that the recoverable fraction of stored thermal energy referenced to a specified reservoir abandonment temperature was about 40%, assuming an idealized, well-defined hydrothermal reservoir with homogeneous properties. To be conservative for EGS systems, the analysis applied the Sanyal and Butler model with lower recovery factors, namely, 20% and 2% to represent an appropriate range of values that might be deliverable in practice. Recovered thermal energy was calculated from the initial amount contained in specified 1 km-thick, horizontal rock slices at initial temperatures given in Chapter 2 and for a specified abandonment temperature that was 10°C below the initial temperature. The temperature-depth maps (Figure 2.7) were used for estimates of the total stored thermal energy. The recovered thermal energy was then converted to electric energy, using an overall heat-to-power cycle efficiency as discussed in Chapter 7 for binary and flash-steam cycles.

To get a better idea of the potential power supply available in the near future, the EGS resource was divided into two parts: 1) a portion associated with hydrothermal systems at depths shallower than 3 km, and 2) the remaining resource at depths between 3 and 10 km as estimated in Chapter 2. Cost of generated power was calculated for each of these two types of EGS resource, using the GETEM code developed for geothermal power costing for the U.S. DOE Geothermal Technologies Program (see Chapter 9, section 9.10.1 for more details).

3.2 Resource Base vs. Reserves

It will be helpful to review the way reserves are treated by the oil and gas industry before addressing this subject for EGS. In the energy industry, the estimated amount of oil or gas available with current technology at today's energy prices is often referred to as the reserve. Reserves clearly are much smaller than the resource base; but, in general, reserve estimates will increase as extractive technology improves and/or energy prices increase. For instance, in most deep sedimentary rock, there is some methane dissolved in the water found in the pores of the reservoir rock. This dissolved gas can be considered part of the natural gas resource base. If we calculated all of it contained in subsurface rock, a large amount of energy would be contained in this resource. Today, dissolved methane is usually not included in natural gas reserve estimates, because it is too dilute and/or too expensive to extract.

An excellent example is U.S. geopressured resources that contain a substantial amount of methane as part of their resource base (see Section 2.6.3). If technology were to improve so that dissolved methane could more easily be extracted, the methane contained in geothermal fluids, in general, could be included in reserves estimates. Similar analogies can be drawn using methane trapped in gas hydrates found in permafrost and marine sediments, or regarding the uranium dissolved in seawater as part of the uranium resource base.

U.S. oil and gas reserves correspond to economically extractable resources as specified by the Securities and Exchange Commission (SEC) Staff Accounting Bulletin, Topic 12 (2006). Given that oil and gas prices fluctuate on the commodity market, the competitive price levels are subject to change. When the price of oil was low a few years ago, thousands of small "stripper" wells in the United States were shut in. The oil and gas contained underground, which is connected to these wells, is still regarded as part of the reserves and included in estimates of what would be available but was not economic to produce at the market price at that time.

Reserve estimates made by the oil and gas industry are further categorized as proven, probable, and possible. The methods for accounting for these reserves are governed by the rules of the SEC (2006). Proven reserves exist where there is a sufficient body of supporting data from geology, geophysics, well tests, and field production to estimate the extent of the oil or gas contained in the body of rock. They are deemed, "commercially recoverable, from a given date forward, from known reservoirs and under current economic conditions, operating methods, and government regulations." Proven reserves can be developed or undeveloped. Probable reserves are unproven reserves, but geological and engineering data suggest that they are more likely than not to be recoverable. Statistical methods are often used in the calculation of probable reserves, and the deciding criterion is usually that there should be at least a 50% probability that the quantities actually recovered will "equal or exceed the sum of estimated proved plus probable reserves." Probable reserves can be in areas adjoining proven or developed fields or isolated from developed fields, but with drilling and testing data that indicates they are economic with current technology. Possible reserves are unproved reserves that are less likely to be recoverable than probable reserves, based on geological and engineering data analysis. Statistically, they are defined as reserves that, if recovered, have – at most – a 10% probability of equaling or exceeding the sum of the estimated proven, probable, and possible reserves. Possible reserves have few, if any, wells drilled; and the reservoir has not been produced, or even tested. However, the reservoir displays favorable geology and geophysics, and its size is estimated by statistical analysis. Possible reserves can also be in areas with good data to indicate that oil and gas are present, but they may not be commercially developable, or the technology to develop them may not exist (but such technology improvements can reasonably be expected in the future). Although this sounds very speculative, there is such a long history of oil and gas production that these estimates are regarded with a fair degree of confidence.

With regard to hydrothermal geothermal resources, some fields have been drilled and produced, so there are supporting data to make assessments of proven, probable, and possible reserves. Of course, even here there is some degree of speculation because no hydrothermal fields have been depleted of heat down to the point where they are uneconomic to produce. However, because EGS is an emerging technology that has not been produced commercially, the level of speculation and uncertainty is even higher – too high, in fact, to regard any of the EGS resource base as economic reserves at this time. EGS should to be classified as a "possible" future reserve.

Obviously, there are no commercial EGS reservoirs and no past production history on which to base recovery calculations. Even hydrothermal reservoirs have not been produced to the point where the amount of heat recovered from the rock volume can be accurately calculated. Nonetheless, we have attempted, as a part of our assessment of EGS, to develop a rationale and methodology for making such an estimate. To do this, we used a combination of the experience from hydrothermal power production projects, numerical modeling, and reasonable constraints regarding how we expect the system to operate for determining what fraction of the total EGS resource might be recovered.

3.3 Metrics that Influence the Recoverable Resource

The EGS resource base heat-in-place estimates developed in Chapter 2 are made by assuming a volume of rock with an average rock density, heat capacity, and a minimum reference temperature. For this assessment, the average surface temperature was used to define the minimum reference temperature. To determine the amount of that heat that can be mined, it is also necessary to include several other important parameters. The initial temperature of the rock at depth determines not only how much thermal energy is in place, but also the rate at which it can be recovered. In addition, a final useful production temperature must be specified for that application. This temperature is referred to as the "abandonment temperature" and represents the average temperature of the active reservoir rock volume at the time heat-extraction operations cease.

The volume of rock that can be fractured and the average spacing between the fractures, along with their length and width, will control the effective heat-exchange area of the reservoir. These, in turn, will determine the rate of energy output and the life of the reservoir. Reservoir volume and the effective surface area available for heat transfer will also affect the fraction of the thermal energy stored in the reservoir that can be extracted over time. The rate at which water – the heat transfer medium – is circulated through the system is a critical parameter. The flow pattern of water between injection and production wells controls how much of the fractured volume is actually swept by the circulating fluid. The permeability and porosity of the fractured volume determine the amount of water stored in the rock, as well as how fast it can move through the rock and with what amount of pressure drop. The circulating water exists at a representative temperature that is taken to be the average temperature of the rock. Also important, the actual flow pattern of fluid in the reservoir is influenced by the spatial distribution of permeability and porosity, as well as the relative positions of the production and injection wells.

3.3.1 Temperature

The resource base figures in Chapter 2 represent the total stored thermal energy in place, relative to the ambient regional surface temperature, T_o. We can define the recoverable fraction of that thermal energy, F_r, as a function of several independent or specified variables, such that:

$$F_r \equiv \frac{Q_{rec}}{Q_{total}} = f[V_{active}, V_{total}, C_r, T_{r,i}, T_{r,a}, T_o] \tag{3-1}$$

$$F_r = \frac{\rho V_{active} C_r (T_{r,i} - T_{r,a})}{\rho V_{total} C_r (T_{r,i} - T_o)}$$

$$F_r = \phi_v \frac{(T_{r,i} - T_{r,a})}{(T_{r,i} - T_o)}$$

where

Q_{rec} = recoverable thermal energy content of the reservoir

Q_{total} = total thermal energy content of the reservoir

ϕ_v = active reservoir volume/total reservoir volume

ρ = rock density (kg/m^3)

V_{total} = total reservoir volume (m^3)

V_{active} = active or effective reservoir volume (m^3)

C_r = rock specific heat (J/kg °C)

$T_{r,i}$ = mean initial reservoir rock temperature (°C)

T_o = mean ambient surface temperature (°C)

$T_{r,a}$ = mean rock temperature at which reservoir is abandoned (°C).

The rate of heat extraction from the rock depends on the difference between the temperature of the rock and the temperature of the circulating water at any point within the reservoir. The larger this difference, the more quickly heat will move from the rock into the water and, in the end, the more heat that can be extracted from the rock. On the one hand, if the cool injected water reaches the production well without being sufficiently heated, the total amount of heat mined from the rock will be less than expected, and the project will not achieve its design conditions. On the other hand, if there is no decline in produced fluid temperature over time, then the flow rate is not high enough to efficiently mine the heat contained in the rock. And, again, the project will not be economically optimized because less total thermal energy will be recovered.

Ideally, we want to maximize the total amount of useful energy extracted from the reservoir. The total energy extracted is given by the time integral over the production period of the instantaneous rate of heat extraction from the rock. For an EGS reservoir, the heat extraction rate is equal to the product of the mass flow rate and the specific enthalpy difference between the produced and reinjected fluid. If we increase the mass flow rate too much, the produced fluid temperature and its specific enthalpy will both decline, offsetting a potential increase in heat extraction rate. At some mass flow rate, an optimal balance is achieved between heat extraction rate and thermal drawdown rate.

In addition, there are issues concerning the efficiency of converting the extracted thermal energy to electrical energy. If we had a completely flexible power-conversion system that could use any temperature of fluid to generate electric power or extract usable heat – although at varying efficiency – we could cool the rock significantly and continue to use the same surface equipment. Real electric-generating power plants, heat pumps, or heat exchangers are designed for a specific set of conditions. The larger the difference between design conditions and actual operating conditions, the less efficient the equipment will become. This places a practical lower limit on the circulating fluid temperature, and consequently a lower limit on the average temperature of the rock in contact with the fluid. We call this latter temperature the "reservoir abandonment temperature," $T_{r,a}$.

The thermal drawdown that occurs in a reservoir will be confined to a localized rock volume defined, in part, by the positions of the injector and producer wells in the stimulated region. The approach for restoring plant output when the thermal drawdown becomes too large will be to drill new infill wells into parts of the field that have not been exploited. This strategy has worked for hydrothermal systems and should work for EGS as well. There will come a time when old wells will be abandoned or redrilled, or new wells added.

Assuming that an EGS reservoir consists of discretely fractured flow paths with average spacings of 100 m or less, then some simplications can be made. Because of the low thermal diffusivity of rock (of order 10^{-6} m^2/s), most of the temperature drop in the reservoir occurs near the injection well and adjacent to the fracture faces in contact with the flowing fluid. If the reservoir rock temperature drops only 10°C on average, there would be ample energy left in the reservoir for future use with equipment designed to operate at lower temperatures, which would increase the sustainability of the resource for the longer term. For instance, a cube of rock 1 km on a side at 200°C would contain 4 x 10^{14} kJ of thermal energy relative to the ambient surface temperature. However, if the average reservoir rock temperature is dropped only 10°C, the heat recovered from that mass of rock would be 2.5 x 10^{13} kJ, leaving about 95% of the original energy in place for later exploitation.

As discussed earlier in this chapter, following active heat-mining operations, production flow and heat removal would cease, allowing rock temperatures to fully recover by conduction in less than 100 years (Elsworth, 1989). This would permit EGS energy recovery to operate sustainably into the future. To be conservative, we specified an abandonment temperature of only 10°C lower than the initial rock temperature in estimating the recoverable energy fraction.

3.3.2 Fractured rock volume

While solid rock is excellent for storing heat, the rate of heat removal by conduction is slow, as a result of its low thermal conductivity. Only that fraction of the rock volume made accessible by the stimulation process can be considered part of the active reservoir where heat extraction occurs. The basic idea is to create permeability and porosity by hydraulic stimulation to open up channels for fluid to circulate through the rock, thereby shortening the rock conduction path. The transfer of heat in such a porous/fractured rock reservoir is a complex process that is not easy to model analytically. Sanyal and Butler (2005) have done sensitivity studies of the impact of various reservoir properties such as fractured volume, fracture spacing, permeability, porosity, and well configuration on the recovery fraction of heat-in-place using 3-dimensional finite element modeling. They varied the permeability, flow rate, fracture spacing, well spacing, injector-to-producer pattern, and fractured volume. They found that the single most important parameter affecting how much of the thermal energy that could be recovered is the fractured volume. In fact, perhaps the most important finding of their study is that the net electrical power that can be achieved from a volume of fractured rock is roughly 0.026 W_e/m^3 (26 MW_e/km^3). This factor applies to a wide variety of production-injection well arrangements (doublets, triplets, five-spots), fracture spacings (3-30 m), and permeability (10-100 mD). The factor seems to hold constant to within about 5%. It also includes reasonable estimates for parasitic power requirements for circulating the fluid through the reservoir.

Based on early field testing of EGS concepts, the geometric arrangement of the production and injection wells, to a large degree, influences the amount of rock that can be stimulated, and the accessible volume of rock that the circulating fluid contacts. EGS wells could be configured in a variety of ways: e.g., with one producer for every injector (a doublet), two producers to each injector (a triplet), or four producers to each injector (the classic five-spot pattern used in enhanced oil recovery operations). The stress regime in the rock volume will determine the fracture pattern and direction, and this will influence the optimal arrangement of injectors and producers. However, having more than one producer for each injector reduces the amount of "dead" fractured volume, in which the rock is fractured but the fluid doesn't circulate. See Chapter 5 for more details.

3.3.3 Fracture spacing

Earlier researchers cited the importance of reservoir geometric structure on heat-removal effectiveness (see Kruger and Otte, 1972; and Armstead and Tester, 1987). Later, Sanyal and Butler (2005) found that, while the fractured volume had the largest effect on recovery factor of the parameters they studied, fracture spacing also had a measurable impact because it is part of determining the active reservoir volume. They investigated fracture spacings between 3 and 300 m. For reasonable fracture spacings of 3 to 30 m that might be realistically accomplished, there is little or no thermal interference, and the fracture spacing is largely irrelevant compared to the total fractured volume in determining how much of the heat-in-place will be recovered. However, for very large fracture spacings (~300 m) and a maximum possible flow rate determined by pump and pressure limitations, the recovery factor using a five-spot pattern with four producers per injector was 2.2%. A smaller fracture spacing of 30.5 m (again using a five-spot pattern and the same flow rate) yielded a 29.4% recovery factor. Lowering the flow rate from 500 kg/s to 126 kg/s per producer (with 30.5 m fracture spacing) increased the recovery factor from 24% to 42.5%, and maintained the reservoir life while still producing economic power output.

Many researchers, typified by the work of Sanyal and Butler, identify fractured rock volume as the single most important parameter affecting thermal recovery. To reach this conclusion, they have implicitly assumed that the rock mass has been homogeneously fractured, which will certainly not be the case in practice. While large surface area and fractured volumes are needed to ensure long-term heat extraction at acceptable rates, their mere existence alone does not guarantee performance. Sufficient fracture density and size are needed and fluid must sweep across the fractured surface area reasonably efficiently for long-term performance to be realized. This has been one of the biggest engineering challenges for EGS, and will be discussed extensively in Chapters 4 and 5.

3.3.4 Fracture surface area

The geothermal reservoir operates like an underground heat exchanger. Injected water is circulated through the reservoir and is exposed to the surfaces of hot rock allowing it to remove heat. The rate of heat transfer – and, consequently, the final temperature that the fluid achieves – is related to the mass flow rate of fluid and the surface area the fluid contacts. The heat-transfer system can be thought of as similar to a series of flat plates with gaps (the fractures) between them and a semi-infinite conduction heat source surrounding each fracture. Heat is transferred by conduction through the rock, perpendicular to the surfaces of the fractures. Then heat is transferred by convection at the rock-fluid interface to the fluid contained in the fracture. The larger that surface area is relative to the flow rate, the faster heat can be transferred to the fluid and still have its outlet temperature approach the original rock temperature with minimal thermal drawdown. (For more details concerning these coupled transport processes, see Armstead and Tester, 1987.) There are several parameters that affect this heat-transfer area:

- Well spacing – This is the distance between the wells in the active part of the reservoir. The well spacing controls the length of the fracture that is actively involved with fluid circulation.
- Fracture spacing – The average distance between fractures that are open and accepting fluid. These are assumed to be connected to the production wells through the fractured rock volume. In reality, these may not act as separate discrete fractures, but as an overall fractured rock mass.

- Fracture length and width – The fracture length is related to, but not necessarily the same as, the well spacing between producer and injector. The fracture is not likely to be a flat plane, but will take a tortuous path through the rock. The path length will, thus, be longer than the well spacing in most cases. The fracture width is the lateral distance that the fracture extends and has active circulation.
- Well configuration – The arrangement of the production wells in relation to the injector. The actively circulated fracture width is controlled, to some extent, by the geometry of the well configuration.

To produce 50 kg/s from a 200°C body of rock, with no more than 10°C temperature drop in the produced fluid over a project life of 30 years, a large rock surface area relative to the mass flow rate of fluid is needed (see Armstead and Tester, 1987). For instance, with eight fractures being used for heat extraction, each must have a length and width sufficient to produce 125,000 m^2 of surface area. If these fractures are 100 m apart, then 700 m or more of wellbore at the 200°C average reservoir temperature is required. To maintain the temperature for a longer life, we would need a longer fracture path length, larger fractures, or more fractures in the wellbore. Real fractures are certainly not the discrete, rectangular channels or circular discs assumed in this simple model. In real situations, fractures often have a greater surface area and path length than the distance between the wells would suggest. At Soultz, for example, in GPK3, about nine open fractures occur in the 540 m open-hole section. However, one fracture at 4,760 m takes 70% of the total fluid flow. This channeling, if left uncontrolled, will effectively reduce the useful recovered thermal energy of the entire reservoir, because heat removal in the fracture that is accepting the higher flow rate is much higher than can be sustained by transient thermal conduction through the surrounding rock.

3.4 Determining the Recoverable Fraction

As discussed above, Sanyal and Butler (2005) have modeled flow in fractured systems to determine the sensitivity of the recoverable heat fraction to several important parameters: rock temperature, fractured volume, fracture spacing, fluid-circulation rate, well configuration, and post-stimulation porosity and permeability. They used a 3-dimensional finite difference model and calculated the fraction of the heat-in-place that could be mined as these important parameters were changed. They found that for a variety of fracture spacings, well geometries, and fracture permeabilities, the percentage of heat recoverable from a stimulated volume of at least 1 x 10^8 m^3 under economic production conditions is nearly constant at about 40%, with a range between 34% and 47% (see Figure 3.1). This recovery factor is independent of well arrangements, fracture spacing, and permeability, as long as the stimulated volume exceeds 1 x 10^8 m^3. This roughly corresponds to a block of rock approximately 500 m x 500 m x 500 m. Because Phase II of the Fenton Hill project, the Rosemanowes project, the Soultz project (both the shallow and deep stimulated volumes), and the Cooper Basin project have achieved fractured volumes based on acoustic emissions mapping of equal to or greater than or greater than 10 x 10^8 m^3 (or 1 km^3), this threshold has already been exceeded in practice.

Because in the early stages of EGS technology development, short circuiting and other reservoir management problems will require extra fractured volume to counter too-rapid temperature drop, it was assumed that two to three times the volume would be needed to guarantee a useful reservoir life. This provides sufficient volume of hot rock for extended development in the event of an irreparable short circuit. However, the excess rock volume effectively halves the recovery factor. The Sanyal and Butler (2005) study found recovery factors that ranged from 2.5% to 90%, with a typical recovery factor of about 45%. Very high recovery factors could only be achieved with uneconomic flow rates or other conditions that resulted in a short reservoir life. Recovery factors from 2% to 40% were therefore used in the calculation of potentially recoverable resources for this study. A recovery factor of 20% was used for Table 3.2 and the supply curves developed in Chapter 9. A 2% recovery factor was used for Table 3.3.

With a recovery factor and an abandonment temperature specified, the recoverable heat can be determined from the total energy in place, i.e., the resource-base amount:

$$Q_{rec} = F_r \, \rho \, V_{total} \, C_r \, (T_{r,i} - T_o). \tag{3-2}$$

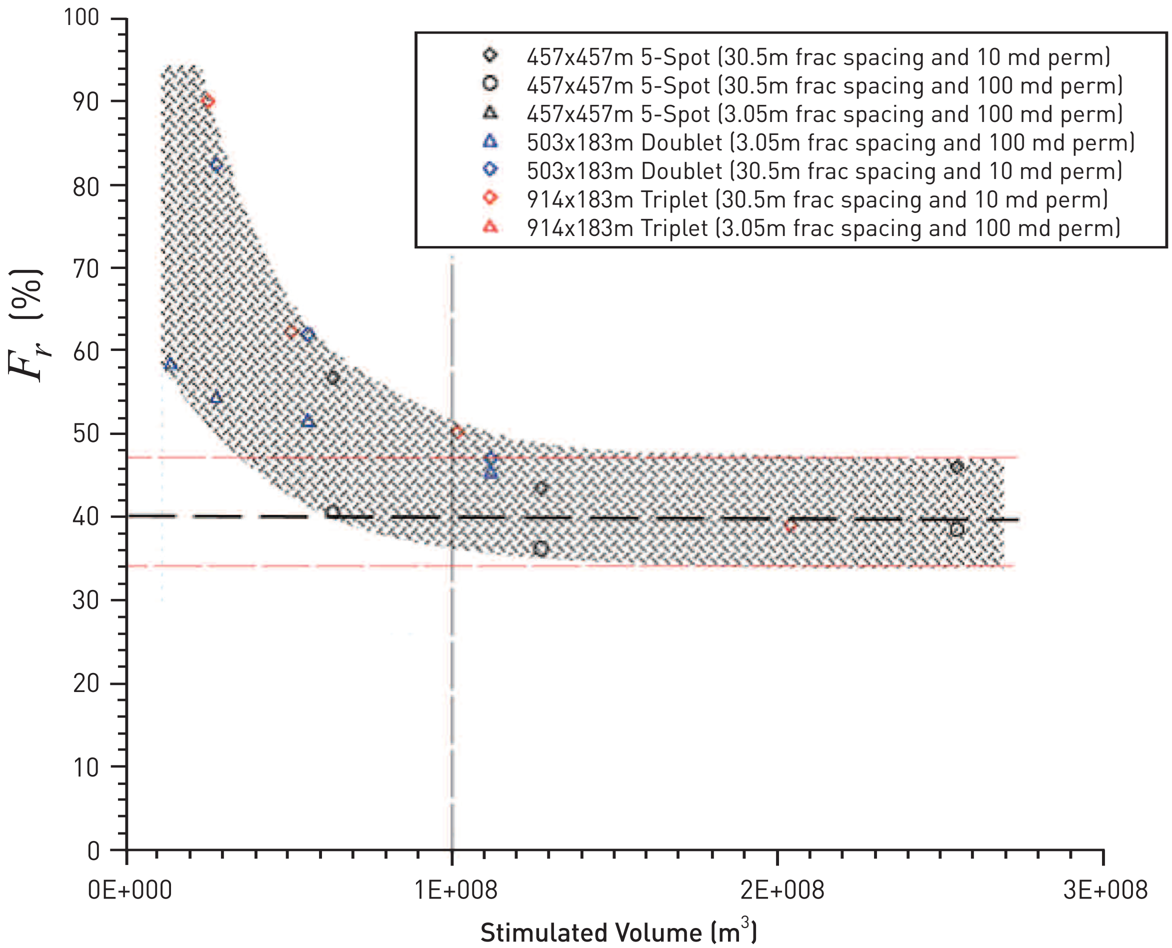

Figure 3.1 Recovery factor vs. stimulated volume for a range of well geometries, fracture spacing, and permeability. (Sanyal and Butler, 2005).

The recovery factor should improve with time as EGS extraction and energy conversion technology matures. The study by Sanyal and Butler (2005) suggests that recoverable energy fractions as high as 45% can be expected with economic flow rates and energy outputs. The analysis assumed an abandonment temperature that corresponds to only a 10°C temperature drop in the rock. There is evidence from 30 years of field testing that strongly suggests that hydrothermal systems achieve recovery amounts for total heat as high as or higher than 45%.

Regarding these estimated recovery factors, it is important to note that they depend strongly on how one defines accessible reservoir volume and characterizes flow through it.

Our ability to create large stimulated rock volumes has certainly improved dramatically. We can now stimulate volumes of 1 km^3 or more. Figure 3.2 shows the stimulated volume for past EGS experimental sites. By developing technology to control flow short circuits and methods to reduce impedances to flow when needed, the fraction of recoverable thermal energy will certainly increase as well.

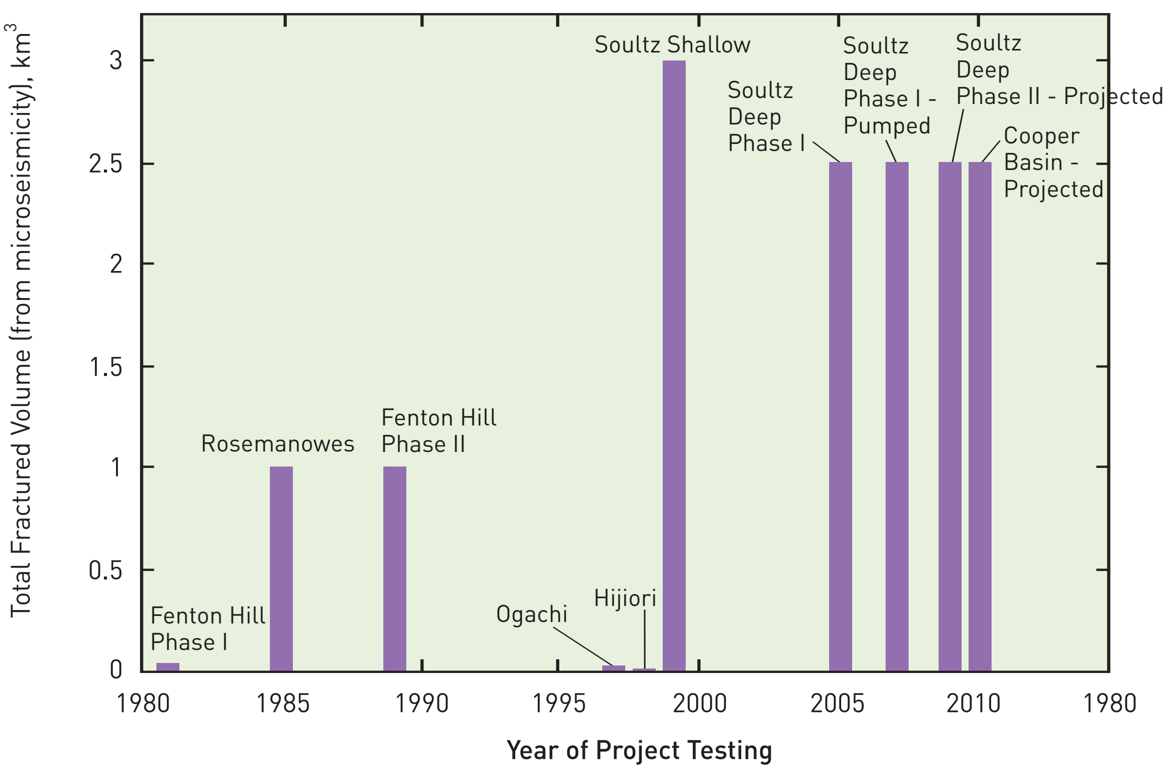

Figure 3.2 Total fractured or stimulated reservoir volume, as determined from microseismic data for representative EGS/hot dry rock (HDR) projects.

3.5 Usable Energy – Converting Heat to Power

Once the amount of recoverable heat from the reservoir has been estimated, it needs to be converted to usable energy, which we assume for this exercise is electricity. Field experience with EGS testing led us to believe that we can extract the heat from the rock for extended periods, with minimal thermal drawdown, if we design and operate the system carefully. As a first approximation, we assume that the production temperature of the fluid at the surface is the average temperature of the rock volume. It is important to note that we are not neglecting the thermal decline within the reservoir that certainly occurs – we are just restricting it to correspond to a specified decline in the average rock temperature at a given depth. Recovered amounts are then estimated from the resource base figures given in Chapter 2 (Figure 2.6) for the conterminous United States.

The power cycle employed, and the ambient surface temperatures along with the fluid temperature, determine the energy conversion efficiency. Chapter 7 discusses power cycles in general, including the conversion efficiency, temperature drop through the system, and other aspects of the conversion of the recoverable heat into electricity. The percentage of heat that can be converted to electricity is quantitatively represented by the thermal efficiency, i.e., the fraction of the total heat delivered to the power cycle by the circulating geofluid that is converted to electrical energy. Thermal efficiencies are based on Figure 7.2 for binary plants at resource temperatures under 200°C, and on the discussion in Section 7.2.2 for flash plants at temperatures above 200°C. The effects of ambient temperature, cooling method, and the power-conversion cycle itself are included. Using the net cycle efficiency allows us to convert the recoverable thermal energy for different temperature resources to electric energy. Table 3.1 shows the utilization efficiencies from Chapter 7 used for this conversion.

Table 3.1 Cycle thermal efficiencies used for energy conversion (see Chapter 7).

Temperature, °C	Cycle Thermal Efficiency η_{th}, %
150	11
200	14
250	16
300	18
350	22

To relate electrical energy to a potential electric-generating capacity, this energy will need to be converted to electric power (power is energy transfer per unit of time). In order to convert electrical energy to electrical power, we need to consider the time over which the energy will be produced. One option is to look at the resource from a project lifetime standpoint. This is the approach used by the United States Geological Survey (USGS) in Circular 790 (Muffler and Guffanti, 1978), where they assumed a project life of 20 years and divided the recoverable energy reserves by the number of seconds in 20 years. Since the time of that report, several geothermal projects have been operated for as long as 30 years, and most project planning for future geothermal projects assumes that each plant will last at least 30 years. Assuming this is the case, the average MW_e of capacity that would result is given by:

$$MW_e = \eta_{th}\, Q_{rec} \times 1MJ/1000kJ \times 1/t \quad (3\text{-}3)$$

where

Q_{rec} = recoverable thermal energy (heat) in kWs (or kJ)

η_{th} = net cycle thermal efficiency (fraction)
t = seconds in 30 years = 30 yr x 365 days/yr x 24 hrs/day x 3600 s/hr. = 9.46×10^8 s

Specifying a recovery factor is arbitrary – however, by assuming a range that spans an order of magnitude and is always lower than the estimates by Sanyal and Butler, we have sufficiently captured the inherent uncertainty in this prediction. The exploitable amount of thermal energy was further reduced by assuming that only a small fraction is actually removed during the period of production to generate electric power. This additional reduction was implemented by specifying a mean temperature of the reservoir at the end of production. This is the abandonment temperature [$T_{r,a}$ in Eq. (3-1)] and had a value of 10°C below the initial rock temperature, $T_{r,i}$.

Table 3.2 shows the recoverable heat as electric power for the United States, assuming a 30-year project life for each depth and average temperature, and a 20% recovery factor. Table 3.3 shows the recoverable heat as electric power using a 2% recovery factor. At only 2% recovery, we note that the 4-5 km deep section of the EGS resource on its own represents an increase of about a factor of 25 over today's U.S. electricity production from geothermal energy. As we go deeper, or increase the recovery factor above 2%, the recoverable electrical power increases proportionally. Going forward, we expect both enhancements to occur as a result of EGS technology improvements from invested R&D and learning curve cost reductions (see Chapter 9 for more details).

Table 3.2 Total recoverable energy in net MW_e for 30 years, with 20% recoverable fraction of thermal energy from the reservoir.

Depth of Slice, km	Power available for slice, MW_e	Amount at 150°C, MW_e	Amount at 200°C, MW_e	Amount at 250°C, MW_e	Amount at 300°C, MW_e	Amount at 350°C, MW_e
3 to 4	122,000	120,000	800	700	400	
4 to 5	719,000	678,000	39,000	900	1,200	
5 to 6	1,536,000	1,241,000	284,000	11,000	600	
6 to 7	2,340,000	1,391,000	832,000	114,000	2,800	
7 to 8	3,245,000	1,543,000	1,238,000	415,000	48,000	1,200
8 to 10	4,524,000	1,875,000	1,195,000	1,100,000	302,000	54,000
TOTAL	12,486,000					

(a) See Table 3.1 for values of the cycle thermal efficiency used.

(b) $T_{a,i} = T_{r,i} - 10°C$, i.e., 10°C below the initial rock temperature [see Eq. (3-1)].

Table 3.3 Total recoverable energy in net MW_e for 30 years, with 2% recoverable fraction of thermal energy from the reservoir.

Depth of Slice, km	Power available for slice, MW_e	Amount at 150°C, MW_e	Amount at 200°C, MW_e	Amount at 250°C, MW_e	Amount at 300°C, MW_e	Amount at 350°C, MW_e
3 to 4	12,000	12,000	80	70	40	
4 to 5	72,000	68,000	4,000	90	120	
5 to 6	154,000	124,000	28,000	1,100	60	
6 to 7	234,000	139,000	83,000	11,000	300	
7 to 8	324,000	154,000	124,000	41,000	5,000	120
8 to 10	452,000	187,000	119,000	110,000	30,000	5,000
TOTAL	1,249,000					

(a) See Table 3.1 for values of the cycle thermal efficiency used.

(b) $T_{a,i} = T_{r,i} - 10°C$, that is 10°C below the initial rock temperature [see Eq. (3-1)].

3.6 Access to the EGS Resource

Only a portion of the total EGS resource will be accessible for development. Urban areas, major roads and utility corridors, as well as national and state parks, recreation areas, wilderness areas, and national monuments will be off-limits for development. Military bases, while possibly accessible for EGS development, are currently treated in a different way from other federal lands – development is severely restricted and royalty structure is different from public or private lands. The panel recommends that these restricted areas should not be considered as part of the EGS resource base. At this point in the evaluation of EGS feasibility, these off-limit areas have not been mapped and have been excluded from the EGS resource – the one exception was the Yellowstone National Park region, which is not included in the U.S. total or in Wyoming, Montana, or Idaho. Quantifying these restricted areas is an important aspect of resource assessment that should be considered in the future.

For this study, we simplified the analysis. The portion of the EGS resource that was not accessible for development was estimated by taking the total fraction of the land in each state – and for the United States as a whole – that was contained in state and national parks, recreation areas, wilderness, national monuments, and military lands. This fraction was assumed to be the fraction of the EGS resource that was inaccessible for development, and it was subtracted from the total recoverable resource:

$$\text{Accessible } MW_e = MW_e(1 - IF) \qquad (3\text{-}4)$$

where

IF = fraction of the total state or U.S. land area that is inaccessible, as described above, due to being located under a park, wilderness or nature preserve, or military base

MW_e = Calculated electric power capacity accessible if all land area was available for development

The amount of power that could then be considered recoverable and accessible is calculated using Eq. (3-1) to (3-4). For states such as Washington, New York, or California, with a large fraction of the total land contained in national and state parks, recreation areas, wilderness and military lands, the fraction of the resource that is considered inaccessible is more than 5%. For states in the Midwest or Gulf Coast, the fraction is much lower, closer to 1%.

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