GEOTHERMAL POWER GENERATION

A PRIMER ON LOW-TEMPERATURE, SMALL-SCALE APPLICATIONS

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REALITY CHECK

Owners of low-temperature geothermal resources are often interested in the possibility of generating electricity with their resource. This is a natural question given the fact that electricity has been commercially produced from geothermal since 1960 in the U.S. and even earlier in other countries. Although large commercial geothermal power generation is an established industry, the potential for it's successful implementation on a small scale (less than100 kW) is less clear for several reasons:

Lack of available equipment - commercially available equipment for geothermal power generation is designed for utility scale applications in the >100 kW range.

High resource temperature requirements - the lowest temperature commercial geothermal power plant currently operating in the U.S. has a resource temperature of 220^{o}F.

Low plant efficiency - conventional fossil fuel plants operate at high temperatures (1000^{o}F) to increase efficiency. Geothermal power plants operating at low temperatures have low efficiency - often less than 10%.

High water flow requirements - the low plant efficiency leads to the need for very high geothermal flow rates to produce power. A 100-kW plant using a 200^{o}F resource might require as much as 300 gpm.

High parasitic power requirements - the low plant efficiency (due to operation at low temperature) leads to high power requirements to operate plant components such as cooling water pumps, tower fans, feed pumps and well pumps. This consumes a large part of the generated power.

High capital cost - costs for the plant equipment alone are in the range of $1,500 to $3,000 per kW of net capacity. These figures are exclusive of wells and other resource development costs.

Poor electricity market conditions - wholesale rates for electricity in the western U.S. is very low (in the $0.02/kWh range). Under the best of conditions, geothermal electricity can be produced for about $0.04 per kW and in many small, low-temperature applications this will be in excess of $0.10 per kW.

INTRODUCTION

Commercial geothermal power generation is an established industry both here in the U.S. and around the world. Italy was the first country to develop geothermal power commercially in 1914 at Larderello. This was followed by plants at Wairakei, New Zealand in 1958 and at the Geysers in California in 1960 (DiPippo, 1999). As indicated in table 1, the U.S. currently leads the world in geothermal power generation with a total of 2850 MW produced from 203 different plants. These plants are located in California, Nevada, Utah and Hawaii.

Table 1. Summary of Worldwide Installed Geothermal Power Capacity (as of 1998).

Country	MW	No. Units	MW/Unit	Plant Types[1]
United States	2850	203	14.0	DS, 1F, 2F, B, H
Philippines	1848	64	28.9	1F, 2F, H
Mexico	743	26	28.6	1F, 2F, H
Italy	742	na	–	DS, 2F, H
Indonesia	589.5	15	39.3	DS, 1F
Japan	530	18	29.4	DS, 1F, 2F
New Zealand	364	na	–	1F, 2F, H
Costa Rica	120	4	30	1F
El Salvador	105	5	21	1F, 2F
Nicaragua	70	2	35	1F
Iceland	50.6	13	3.9	1F, 2F, H
Kenya	45	3	15	1F
China	28.78	13	2.2	1F, 2F, B
Turkey	21	1	21	1F
Portugal (Azores)	16	5	3.2	1F, H
Russia	11	1	11	1F
Ethiopia	8.5	2	4.2	H
France (Guadeloupe)	4	1	4	2F
Argentina	0.7	1	0.7	B
Australia	0.4	1	0.4	B
Thailand	0.3	1	0.3	B
Total	8147.78			

1. DS = Dry Steam, 1F = Single Flash, 2F = Double Flash, B = Binary, H = Hybrid

Note: A unit is defined as a turbine-driven generator. Data from Ref (4) and various other sources.

Plant Types

There are basically three types of geothermal plants used to generate electricity. The type of plant is determined primarily by the nature of the geothermal resource at the site.

The so-called direct steam geothermal plant is applied when the geothermal resource produces steam directly from the well. The steam, after passing through separators (which remove small sand and rock particles) is fed to the turbine. These were the earliest types of plants developed in Italy and in the U.S. Recent direct steam plants in the U.S., at the Geysers in California have been installed in capacities of 55 and 110 MW. Unfortunately, steam resources are the rarest of the all geothermal resources and exist in only a few places in the world. Obviously steam plants would not be applied to low-temperature resources.

Flash steam plants are employed in cases where the geothermal resource produces high-temperature hot water or a combination of steam and hot water. The fluid from the well is delivered to a flash tank where a portion of the water flashes to steam and is directed to the turbine. The remaining water is directed to disposal (usually injection). Depending on the temperature of the resource it may be possible to use two stages of flash tanks. In this case, the water separated at the first stage tank is directed to a second stage flash tank where more (but lower pressure)steam is separated. Remaining water from the second stage tank is then directed to disposal. The so-called double flash plant delivers steam at two different pressures to the turbine. Again, this type of plant cannot be applied to low-temperature resources.

The third type of geothermal power plant is called the binary plant. The name derives from the fact that a second fluid in a closed cycle is used to operate the turbine rather than geothermal steam. Figure 1 presents a simplified diagram of a binary type geothermal plant. Geothermal fluid is passed through a heat exchanger called a boiler or vaporizer (in some plants, two heat exchangers in series the first a preheater and

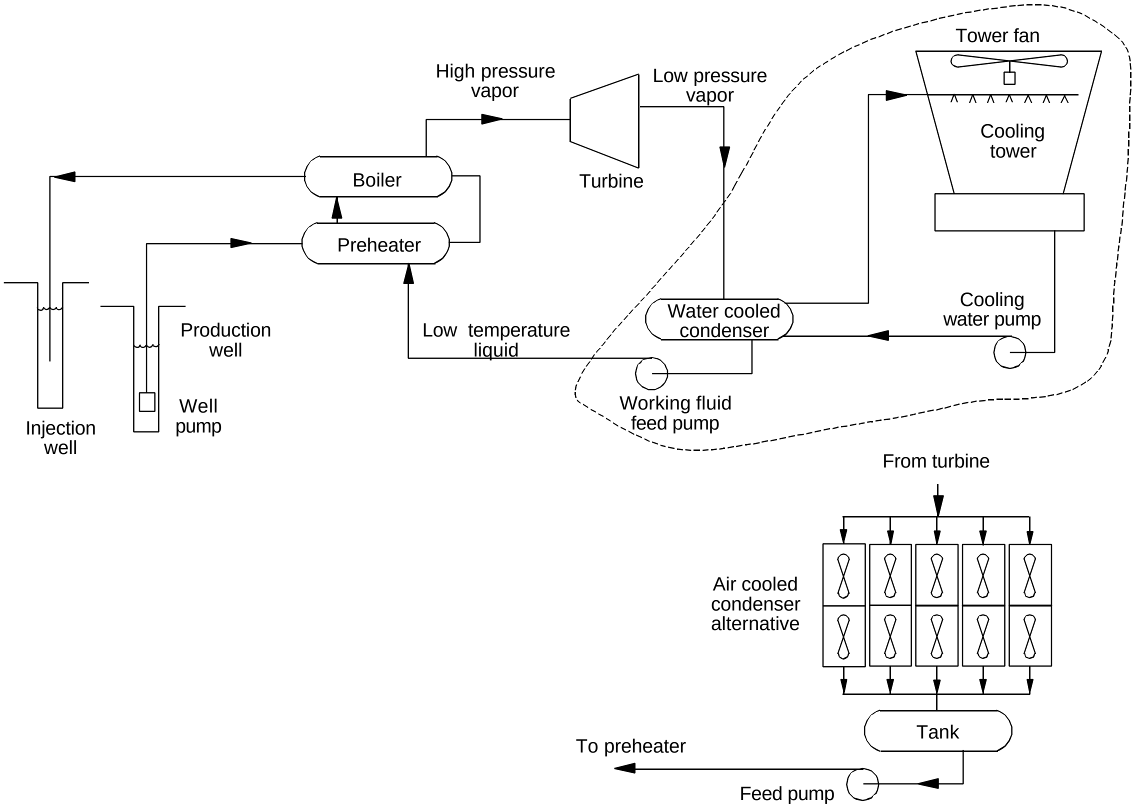

Figure 1. **Binary geothermal power plant.**

the second a vaporizer) where the heat in the geothermal fluid is transferred to the working fluid causing it to boil. Past working fluids in low temperature binary plants were CFC (Freon type) refrigerants. Current machines use hydrocarbons (isobutane, pentane etc) of HFC type refrigerants with the specific fluid chosen to match the geothermal resource temperature.

The working fluid vapor is passed to the turbine where its energy content is converted to mechanical energy and delivered, through the shaft to the generator. The vapor exits the turbine to the condenser where it is converted back to a liquid. In most plants, cooling water is circulated between the condenser and a cooling tower to reject this heat to the atmosphere. An alternative is to use so called "dry coolers" or air cooled condensers which reject heat directly to the air without the need for cooling water. This design essentially eliminates any consumptive use of water by the plant for cooling. Dry cooling, because it operates at higher temperatures (especially in the key summer season) than cooling towers does result in lower plant efficiency. Liquid working fluid from the condenser is pumped back to the higher pressure preheater/vaporizer by the feed pump to repeat the cycle.

The binary cycle is the type of plant which would be used for low temperature geothermal applications. Currently, off-the-shelf binary equipment is available in modules of 200 to 1,000 kW.

POWER PLANT FUNDAMENTALS

Power Plant Components

The process of generating electricity from a low temperature geothermal heat source (or from steam in a conventional power plant) involves a process engineers refer to as a Rankine Cycle. In a conventional power plant, the cycle, as illustrated in figure 1, includes a boiler, turbine, generator, condenser, feed water pump, cooling tower and cooling water pump. Steam is generated in the boiler by burning a fuel (coal, oil, gas or uranium). The steam is passed to the turbine where, in expanding against the turbine blades, the heat energy in the steam is converted to mechanical energy causing rotation of the turbine. This mechanical motion is transferred, through a shaft to the generator where it is converted to electrical energy. After passing through the turbine the steam is converted back to liquid water in the condenser of the power plant. Through the process of condensation, heat not used by the turbine is released to the cooling water. The cooling water, is delivered to the cooling tower where the "waste heat" from the cycle is rejected to the atmosphere. Steam condensate is delivered to the boiler by the feed pump to repeat the process.

In summary, a power plant is simply a cycle that facilitates the conversion of energy from one form to another. In this case the chemical energy in the fuel is converted to heat (at the boiler), and then to mechanical energy (in the turbine) and finally to electrical energy (in the generator). Although the energy content of the final product, electricity, is normally expressed in units of watts-hours or kilowatt-hours (1000 watt-hours or 1kW-hr), calculations of plant performance are often done in units of BTU's. It is convenient to remember that 1 kilowatt-hour is the energy equivalent of 3413 BTU. One of the most important determinations about a power plant is how much energy input (fuel) is required to produce a given electrical output. To make this calculation, it necessary to know the efficiency of the power plant.

Power Plant Efficiency

One of the most important concepts governing the operation of a power plant is that the efficiency of the process is determined by the temperature difference between the boiler and the condenser. For example, in a conventional fossil fuel power plant, the temperature of the steam leaving the boiler may be 1,000°F. The condenser may operate at 100°F. The theoretical efficiency of the cycle may be calculated from the following formula:

$$TCE = \left(\frac{T_h - T_l}{T_h} \right) \times 100 \qquad \text{Equation 1}$$

where: TCE = Theoretical cycle efficiency
T_h = absolute temperature of the steam leaving the boiler °R
T_l = absolute temperature of the condenser °R

Note: Absolute temperature (°R) is determined by adding 460° to the temperature in °F.

Example: A power plant is operated with a steam temperature of 1,000°F and a condenser temperature of 100°F. Calculate the theoretical efficiency.

Ts = 1000 + 460 = 1460 °R
Tc = 100 + 460 = 560 °R

Efficiency = ((1460 - 560)/1460) x 100
= 61.6%

This means that, in theory, 61.6% of the energy contained in the steam would be converted to mechanical energy in the turbine. In a real power plant, due to efficiency losses in equipment and heat transfer processes, only about ½ to 2/3 of this theoretical efficiency is achieved. In other words, the actual efficiency of the power cycle might be about 0.666 x 61.6% or 41% at best. As a result, of the energy contained in the steam, only 41% would be converted to mechanical energy in the turbine and the remaining 59% would be rejected to the atmosphere as waste heat. Beyond the losses in the cycle itself, there is an efficiency associated with the boiler/combustion process and the generator. For a power cycle operating at 41% coupled to a boiler at an efficiency of 85% and a generator at an efficiency of 97%, the combined plant efficiency would be 0.41 x 0.85 x 0.97 = 0.338 or 33.8%. This means that for each kWh produced at the generator in this power plant, a fuel input of 3414/0.338 = 10097 BTU would have to be supplied to the boiler.

In conventional power plants, the temperature at the boiler can be adjusted to any value the designer chooses, within the capabilities of the equipment. This allows the plant to be designed for optimum efficiency. In geothermal power plants, the resource determines the maximum temperature at which the cycle can operate and thus to a large extent, the cycle efficiency. Geothermal resources, even the highest temperature ones, produce temperatures far less than those at which conventional power plant cycles operate at. For example, many geothermal power plants use resources of less than 400^{o}F. Since they reject heat to the atmosphere just as conventional power plants do, the condenser temperature is the same as in the example above. For a direct steam plant, the resulting cycle theoretical efficiency, using these temperatures is:

$$\begin{aligned} \text{Efficiency} &= ((400 + 460) - (100 + 460))/(400 + 460) \\ &= 0.349 \text{ or } 34.9\% \text{ efficiency} \end{aligned}$$

Assuming the same actual performance adjustment used above (66% of theoretical), the actual cycle efficiency would be 23.0%. With generator efficiency of 97% the plant efficiency would be 22.3% (23 x 0.97). The heat input to a plant operating at this level of performance would amount to 3413/ 0.223 or 15305 BTU/kWh. This is approximately 50% more heat input to produce the same output as the conventional power plant in the example above. Of equal importance is the fact that for each kWh produced from the plant, it will be necessary to reject to the atmosphere 15305 BTU x(1- 0.23) or 11784 BTU per kWh. This is 2.4 times the waste heat rejected by the conventional power plant. In terms of the plant this means that the cooling tower and related heat rejection equipment must be correspondingly larger (and more costly) than the same components for a conventional power plant.

To this point the issue of plant or cycle efficiency has been discussed in the context of what is typically referred to as "gross plant efficiency". This simply compares the heat (or fuel) input to the plant to the electrical output of the generator (in equivalent energy units). In all plants, there are electrical loads such as pumps fans and controls which are necessary to operate the facility. Often these loads are referred to as "parasitc loads" - those which consume a portion of the plant's output. Net plant efficiency incorporates the electrical consumption of these devices to arrive at the performance of the plant in terms of net power output actually available to the owner for use or sale (depending upon the arrangement). Net power plant efficiency is always lower than gross plant efficiency since it is based on a smaller (net) output. For example, assume that a particular plant is producing 1000 kW (or 1 MW) and has a total parasitic load for plant equipment of 150 kW. The gross efficiency is 20 %. This would require a heat input of:

$$(1000 \text{ kW x } 3413 \text{ BTU/kWhr})/0.20 = 17{,}065{,}000 \text{ BTU/hr}$$

Allowing for the parasitic loads, the net plant efficiency would be:

$$((1000 \text{ kW} - 150 \text{ kW}) \text{ x } 3413 \text{ BTU/kWhr})/ 17{,}065{,}000 \text{ BTU/hr} = 0.17 \text{ or } 17\%$$

Plant efficiency impacts the feasibility of producing geothermal power in two important ways. As efficiency drops (as a result of lower resource temperature for example), the quantity of heat input required to produce a given output increases resulting in higher costs for resource development. At the same time the quantity of heat input required is increasing, the percentage of that input that must be rejected as waste heat is also rising. This increases the cost of the cooling portion of the plant and increases the parasitic load as well.

The forgoing discussion is valid for direct steam type power plants. In binary plants, the type appropriate to low temperature resources, the temperature of the vapor leaving the boiler is always less than the temperature of the geothermal resource fluid. This temperature difference is necessary to allow the transfer of heat out of the geothermal fluid and into the working fluid. It also has an impact on the efficiency of the cycle since it results in a lower T_h in Equation 1.

Figure 2 is a plot of binary power plant performance based on data from a manufacturer of this equipment (Nichols, 1986). It is apparent that at very low resource temperatures, plant efficiencies are less than 10%, meaning that over 90% of the heat delivered to the machine is rejected to the atmosphere. The values plotted are representative of net plant efficiency exclusive of the well pumping power necessary to produce the geothermal fluid.

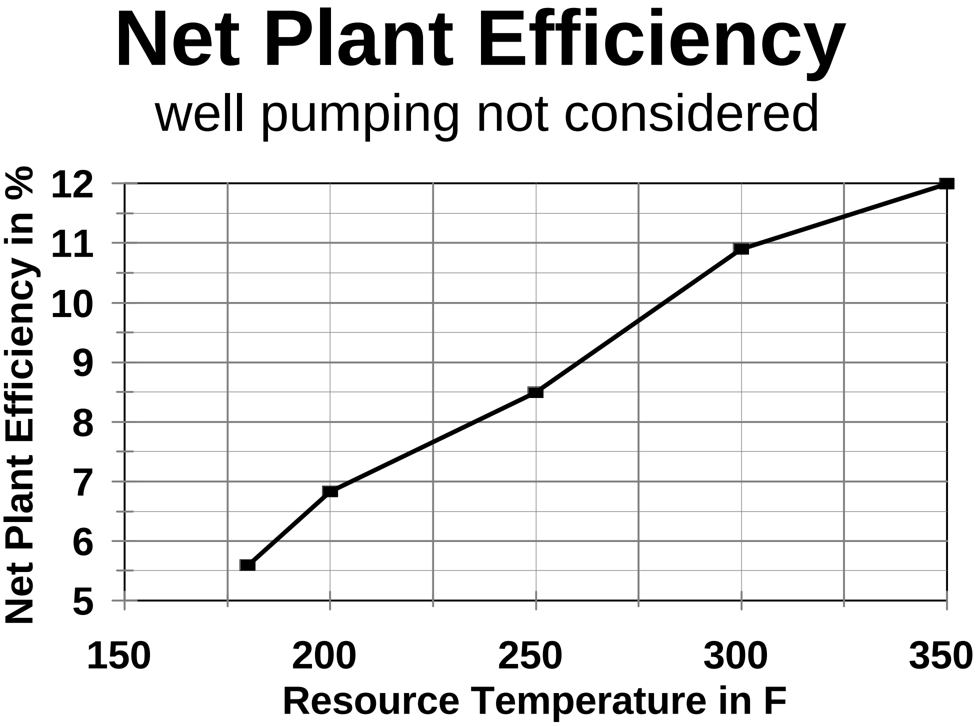

Figure 2 (after Nichols, 1984).

One calculation of interest in the course of evaluating a power generation application is the quantity of water flow required. It is possible to make this determination knowing the desired plant output (in kW or MW), the probable plant efficiency and the resource temperature.

Example:

A binary power plant will be designed to produce an output of 300 kW using a resource temperature of 220°F. What is the approximate geothermal fluid flow required?

From Figure 2 we can determine that the likely plant net efficiency at 220°F would be approximately 7.5%.

The required plant heat input is determined by dividing the output by the efficiency as follows:

= (300 kW x 3413 BTU/kWhr)/ 0.075
= 13,652,000 BTU/hr

The required geothermal water flow can be calculated by dividing the required heat input by 500 x ? T, where ? T is the temperature drop of the geothermal fluid (entering temperature - leaving temperature) in °F. Most binary plants are capable of achieving leaving geothermal water temperatures of approximately 160°F. The entering water temperature can be assumed to be the same as the resource temperature.

Required geothermal water flow = 13,652,000 BTU/hr / (500*(220-160))
= 455 gpm

ECONOMICS

Figure 3 (after Entingh and others, 1994) presents costs for binary type power plants using air cooling for the condenser. Note the impact of resource temperature and plant size on capital cost. A 1-MW plant using a 285°F resource incurs a unit capital cost of approximately $1,780 per installed kW. The installed cost of a 100-kW plant using a 210°F resource is over 60% higher at $2,900. It is important to point out that these costs do not include resource development (exploration, production and injection wells or pumps).

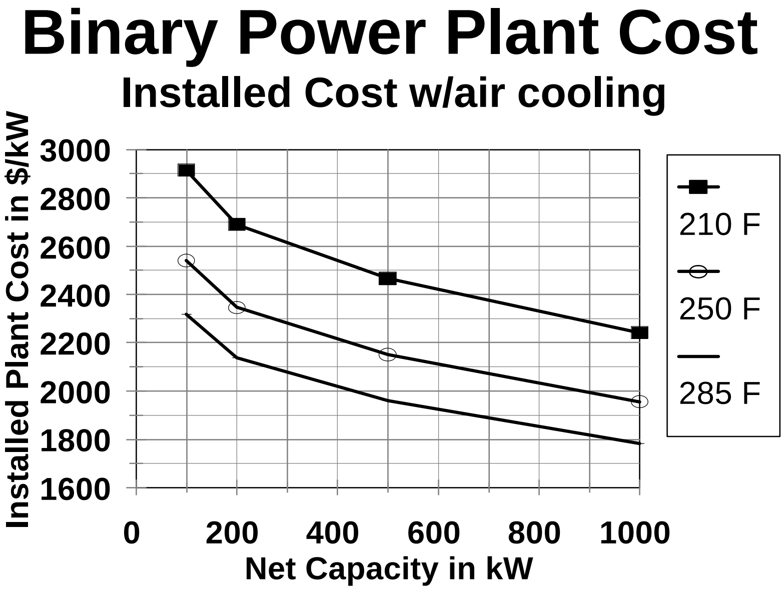

Figure 3 (after Entingh and others, 1994).

In the same work by Entingh and others, costs for electricity produced by a plant with the following description were developed:

Resource Temperature	250^{o}F
Net Capacity	300 kW
Production Well Depth	1,000 ft
Injection Well Depth	650 ft
Capacity Factor	0.80
Service Life	30 yrs
Total Capital Cost (wells and plant)	$1,278,000
Annual Maintenance Costs	$ 63,000
Cost of produced electricity	$ 0.105 per kWhr

In addition, the same authors evaluated the impact of key parameters on the cost of electricity produced. The three most influential parameters, plant size, resource temperature and production well depth are examined in Figures 4, 5, and 6 respectively.

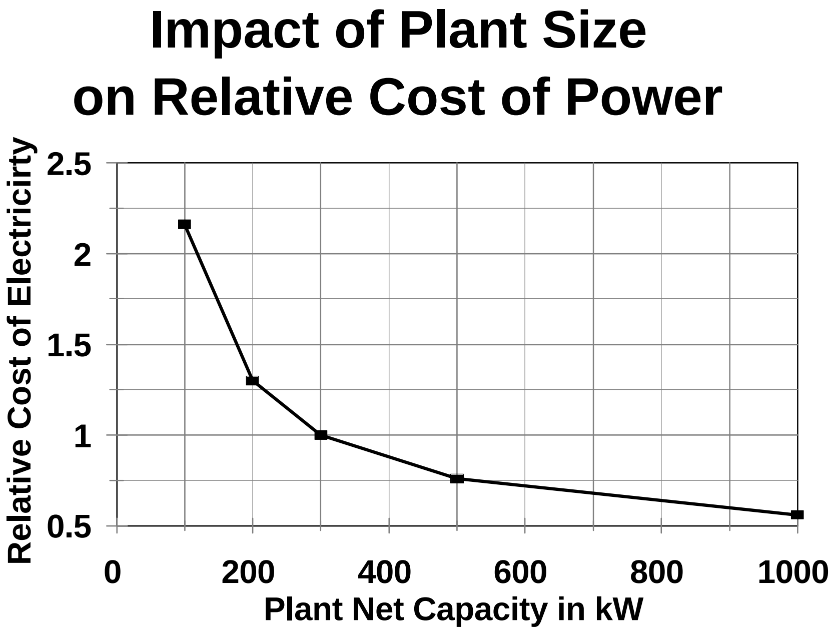
Impact of Plant Size on Relative Cost of Power

Figure 4. (after Entingh and Others, 1994).

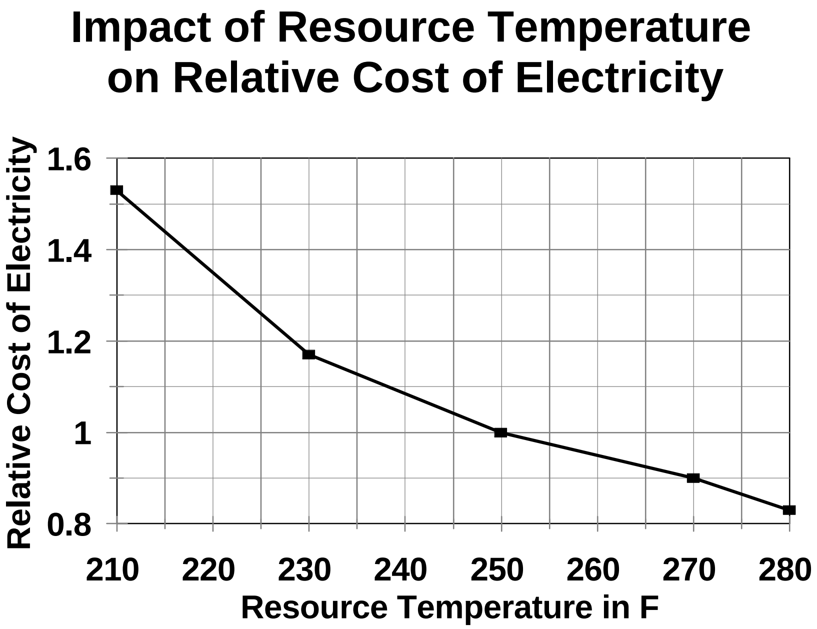

Figure 5. (after Entingh and Others, 1994).

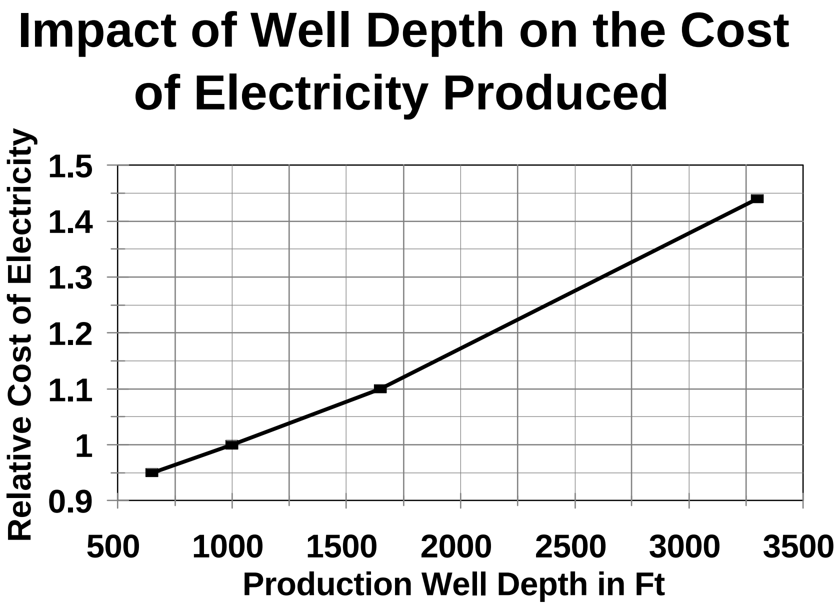

Figure 6. (after Entingh and Others, 1994).

Using the baseline value of $0.105 for the plant described above and multipliers from Figures 4, 5 and 6, it is possible to estimate the cost of power produced from plants under a variety of circumstances. At the one extreme, a 210°F resource supplying a 100-kW plant from a 3,000 ft deep production well would result in a cost of electricity of:

$$\$0.105 \times 1.53 \times 2.16 \times 1.38 = \$0.479 \text{ per kWh}$$

At the more favorable end of the spectrum, a 280°F resource supplying a 1,000-kW plant from a 1,000 ft deep production well would result in a cost of electricity of:

$$\$0.105 \times 0.83 \times 1.0 \times 0.56 = \$0.049 \text{ per kWh}$$

It is apparent that low temperature application of binary power in very small plant sizes is unlikely to be competitive with other sources of electricity in most applications.

Potential developers of small geothermal power systems sometimes over look the importance of the issue of capacity factor in the evaluation process. The above costs for the production of electricity incorporated a capacity factor of 0.80 or 80 %. This means that the plant, on an annual basis is operating 80% of the available hours (0.80 x 8760 = 7008 hrs) at it’s rated net capacity. For a 100-kW plant, this would mean an annual production of 7008 hrs x 100 kW = 700,800 kWh. Since the cost of producing each kWh is determined by dividing the total costs for owning and operating the plant by the total number of kWh produced, the cost per kWh is inversely proportional to the capacity factor.

The importance of this becomes apparent when a potential developer is considering using the binary plant to produce power for internal use at a facility instead of for sale to a utility. When power is sold to a utility or outside entity, the full capacity of the plant can be utilized on a continuous basis. When generating power for internal use only, the output of the plant follows the load of the facility. As a result, the load factor of the plant would equal the load factor of the facility. This value is normally far less than that which would be achieved by a plant generating power for outside sales. The result is a higher cost of power produced.

CONCLUSIONS

At the present time, the generation of electricity using low to moderate temperature geothermal resources is an established technology. Successful applications in the U.S. are characterized by resource temperatures of greater than 220°F, plant sizes of greater than 0.5MW (500 kW) and sales to a utility (as distinct from generation for on site use). The application of this technology to lower resource temperatures or in very small plant sizes, absent unusual considerations, while technically feasible, is unlikely to be a wise economical choice for the owner.

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