Electrical Generating Capacities of Geothermal Slim Holes

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ABSTRACT

A growing market exists for off-grid electrification projects in the developing countries of the world. Small wellhead geothermal generating plants (from 100 to 1000 kW electrical capacity) could supply these needs in nations with geothermal potential. Theoretical calculations are presented to estimate the electrical generating capacity of the hot fluids discharged from individual geothermal wells, particularly slim holes, over a wide range of reservoir and operating conditions. Slim holes (75 to 150 mm in diameter) can provide enough hot geofluid for such projects, and can also substantially reduce project costs and adverse environmental effects. The study examines both self-discharging wells and wells equipped with downhole pumps, as well as a variety of design concepts for the surface generating equipment (including flash-steam and binary systems). Resource temperature is the single most important parameter influencing electrical capacity. A downhole pump will usually be required if the reservoir temperature is below 150°C or so. Downhole *submersible* pumps are preferable to conventional *lineshaft* pumps for slim-hole applications. Downhole pumps cease to be advantageous (compared to self-discharge) above ~200°C for standard production wells and above ~160°C for slim holes. Wells as small as 75 mm diameter can supply enough fluid to generate 100 kW of electricity so long as reservoir temperatures exceed 170°C, and can attain 600 kW if temperatures reach 240°C. Larger (150 mm diameter) slim holes can provide over 1000 kW for resource temperatures above 180°C and can reach 3000 kW for a 240°C fluid supply.

Introduction

Small geothermal generating plants (100 to 1000 kW capacity) offer much promise for rural electrification in various areas around the world, particularly Latin America, Indonesia, the Philippines, Africa, and isolated islands. Typically, these remote-area installations would consist of single production wells driving generating equipment located immediately adjacent to the wellhead. Entingh *et al.* (1994) examined the economic feasibility of such projects and concluded that small plants of this type can compete favorably with existing off-grid electrification techniques in this capacity range (mainly diesel generators), and also with other proposed renewable energy sources (photovoltaic solar, wind, hybrids).

Larger (5,000-10,000 kW) off-grid geothermal projects are feasible using one or two standard size production wells driving a small wellhead power plant. Steam turbines are usually used for relatively high-temperature systems (reservoir temperature over 200°C or so). Binary plants are usually used for lower-temperature systems and a downhole pump will be required in the production well(s) to maintain discharge and sufficient pressure to assure single-phase flow in the heat exchanger.

For smaller projects (100-1000 kW), the costs of drilling and completing the production well dominate the economics. Entingh *et al.* assumed that the well would be drilled using conventional techniques: 340 mm OD *("outside diameter")* casing to 230 meters depth and 245 mm OD casing below that depth. If a slim hole could be used instead, considerable savings in drilling costs and final electricity price would be realized. All else being equal, the cost of drilling a geothermal well to a particular depth increases roughly in proportion to well diameter (Combs and Dunn, 1992). For remote applications, the portability of small rigs will further reduce costs (it is even practical to transport slimhole rigs by freight helicopter). Also, the environmental impact and land-use requirements of slim-hole drilling operations are generally much more acceptable than conventional drilling.

The central issues are: (1) can slim holes deliver enough hot fluid to be of practical use? (2) If so, what are the relationships between well diameter and generating capacity? Here, results of a theoretical investigation of these issues are summarized. The study was supported by the U.S. Department of Energy: the final report (Pritchett, 1998) is over 3000 pages long and provides detailed quantitative results. In this paper, attention is restricted to presentation of the general methodology employed and a sampling of pertinent conclusions.

First, discharge characteristics of geothermal production wells (relationships among wellhead pressure, well mass discharge rate, and wellhead enthalpy) are described as functions of (a) well diameter and depth, and (b) reservoir temperature, pressure, gas content, and permeability. Attention is restricted to reservoirs which contain liquid water only (no steam) at the feedpoint depth. Both self-discharging wells and wells containing downhole pumps are studied. Then, the electrical generating capacities of these hypothetical wells are appraised. Electrical generating capacity depends upon (1) the well and reservoir description (well diameter and depth; reservoir temperature, pressure, gas content and permeability), (2) the presence or absence of a downhole pump (and, for pumped wells, the type of downhole pump employed), and (3) the characteristics of the wellhead power plant. Several different types of wellhead plants are considered, including single-flash steam plants (backpressure and condensing type), double-flash steam plants, binary plants, and steam/binary hybrid designs.

All wells are considered to be of uniform inside diameter *(ID)* and vertically oriented. ID values range from 75 to 300 mm. Well feedpoint depths from 300 m to 1200 m are considered. Reservoir temperatures (stable shut-in temperatures at the well feedpoint depth) range from 100 to 240°C. Reservoir fluids vary between pure H_2O and a 1% (by mass) solution of dissolved CO_2 gas. Reservoir permeability is characterized by the productivity index, from 20 kg/s per MPa to infinity. Reservoir pressure is described by *piezometric surface depth* (between zero and 250 m) - the depth at which a hydrostatic pressure distribution (gradient corresponding to water density at the feedpoint temperature) which passes through the stable shut-in feedpoint pressure would reach one atmosphere.

Two kinds of downhole pump are available for geothermal service: *lineshaft* pumps in which a wellhead electric motor drives the downhole pump body using a long concentric rotating shaft, and *submersible* pumps in which the motor is also located downhole (Figure 1). The fluid emerging from self-discharging wells is a mixture of water and steam; the evolution and expansion of steam provides the lift to raise the boiling mixture to the surface. If a downhole pump is installed, compressed liquid water is driven upward through a sealed pipe (the *column,* which fits within the well casing) under sufficient pressure that the fluid flowing from the wellhead remains single-phase-liquid. This is necessary to avoid scaling in the column. The annular region between column and casing is filled with high-pressure static steam.

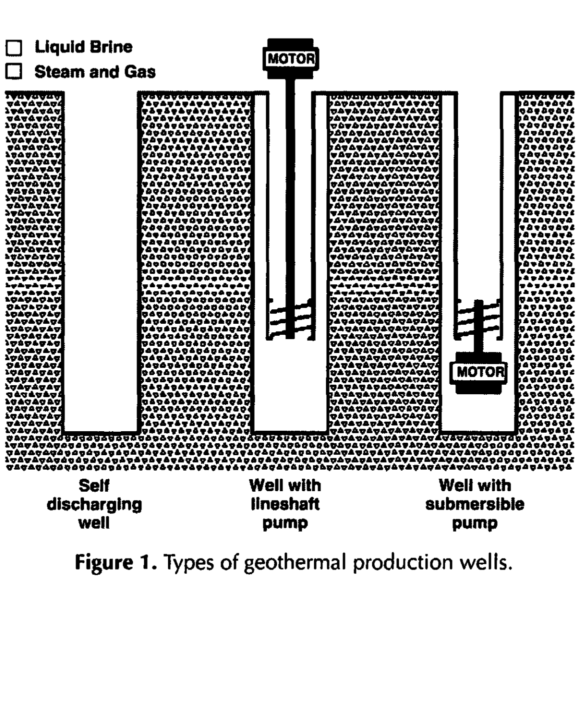

Figure 1. Types of geothermal production wells.

Self-Discharging Wells

Theoretical calculations of steady flow up self-discharging wells were carried out using the well-verified WELBOR numerical simulator (Pritchett, 1985). In WELBOR,

- *feedpoint conditions* are calculated from stable reservoir conditions assuming isenthalpic single-phase flow with pressure decline dictated by productivity index,
- *pipe friction* (single- and two-phase) is treated using the method of Dukler *et al.* (1964),
- *velocity difference* between water and steam is treated using the holdup correlation of Hughmark (1962), and
- *lateral heat loss* to the formation is treated using a procedure (Pritchett, 1993) based on the thermal boundary layer analysis of Minkowycz and Cheng (1976).

WELBOR calculates flowing conditions inside the borehole by integrating equations representing mass, energy and momentum conservation from the feedpoint up to the wellhead for a specified total mass flow rate. By repeating the calculation for various flow rate values, the *discharge characteristics* (the relationships among wellhead total mass flow rate, wellhead pressure, and wellhead discharge enthalpy) may be obtained. Calculated discharge characteristics for a particular case (150 mm ID, 600 m feedpoint depth, 100 m piezometric surface depth, 200°C reservoir temperature, and no reservoir CO_2) are shown in Figure 2. For this particular case, the maximum attainable wellhead pressure (P_{max}) is 0.69 MPa and the maximum flow rate (F_{max}) is 28 kg/s (Figure 2A).

Calculations of this type were performed for a variety of values of the free parameters involved. If the productivity index is high enough, the maximum discharge rate F_{max} increases with $ID^{2.5}$ (also see Pritchett, 1993). Lower productivity index values reduce attainable flow rates, particularly for large-diameter wells. Both P_{max} and F_{max} tend to increase with increasing reservoir temperature, pressure, and/or reservoir CO_2 content. Discharge enthalpy declines with decreasing flow rate (Figure 2B) because of lateral heat losses, due to the longer residence time of an element of fluid within the well. This effect increases for deeper wells (longer residence time), and smaller ID wells (larger surface/volume ratio).

Wells with Downhole Pumps

If reservoir temperature is low, it will often be necessary to apply a downhole pump. Experience with downhole geothermal pumps in slim holes is sparse, so a separate study was carried out to estimate the fluid-delivery and power-consumption characteristics of downhole pumps that could be constructed for slim-hole geothermal applications based on existing technology (Pritchett, 1997). Mathematical models were devised to

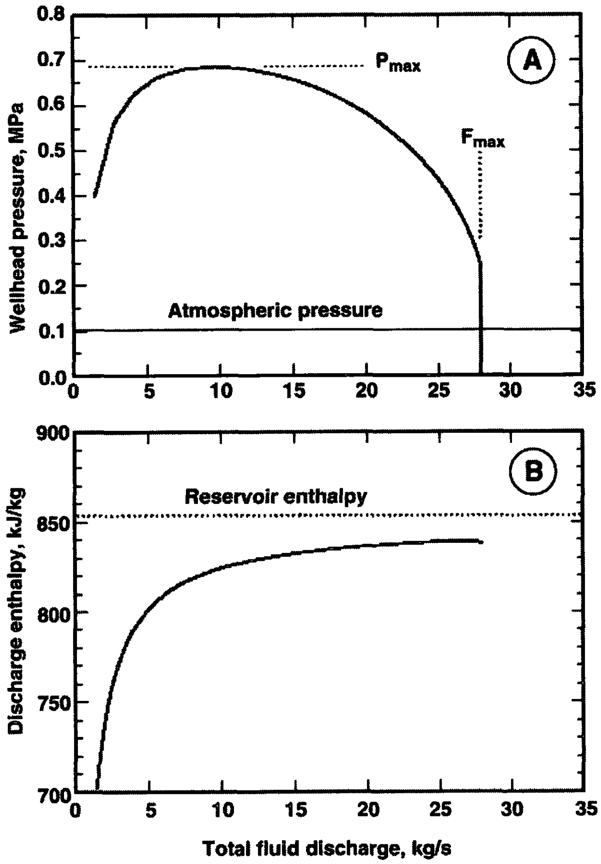

Figure 2. Wellhead discharge characteristics.

describe the performance of downhole geothermal pumps under a variety of conditions. The models are based on (1) performance characteristics of existing downhole pumps as described in the catalogues of various downhole pump suppliers, (2) consultation with geothermal developers who rely on downhole pumps for the success of their projects, and (3) advice from acknowledged experts in downhole pump design.

Most practical experience for geothermal applications is with lineshaft pumps (with motor located at the wellhead), but in recent years geothermal applications of submersible pump designs have begun. In either case, the pump assembly consists of (1) a number of *bowl/impeller* assemblies (or *stages*) arranged in series, which supply fluid to (2) the *column*, a sealed pipe which delivers pressurized brine to the wellhead. Lineshaft pumps usually use a four-pole (1800 RPM) wellhead motor, whereas downhole motors installed in submersible pumps are usually of two-pole (3600 RPM) design.

The pump inlet must be located slightly below the level within the well where the rising fluid would otherwise start to boil, to avoid pump cavitation, loss of head, and damage. The *pump head* (the total pressure increment imparted to the rising fluid by all of the pump stages) must be sufficient to maintain the flowing wellhead pressure above the bubble point. This requirement dictates the number of stages that are needed. The mathematical model incorporates representations for the pump discharge rate, hydraulic efficiency, and pump head per stage attainable for both submersible and lineshaft designs as functions of well ID. Additional design constraints are also incorporated, such as limitations on the pressure difference across the column wall, the maximum number of stages that may be assembled, effects of material-strength issues on lineshaft length and on maximum lineshaft motor power, and maximum temperatures and electric power for submersible motors. Well diameter generally influences these issues.

The studies (Pritchett, 1997; 1998) indicate that lineshaft pumps provide somewhat better fluid delivery capacity for wells over 250 mm ID or so, but that for smaller diameter wells submersible pumps will provide higher fluid discharge rates and can operate at higher reservoir temperatures. Lineshaft pumps which will fit in wells less than 200 mm ID are impractical for geothermal service, whereas submersible pumps have been installed in wells down to 150 mm ID, and smaller designs are possible. The slight advantage of the lineshaft design for large-diameter wells arises from present-day power limitations on submersible pump motors. Significant advances in downhole motor technology have been achieved in recent years, and are likely to continue in the future. By contrast, lineshaft pump technology is mature and essentially static. For these reasons, it was assumed that submersible pump designs would be applied to slim holes when pumping is needed for small geothermal off-grid electrification projects.

Parasitic loads required to operate the downhole pump must be deducted from the electrical capacity of the wellhead power plant. Account must be taken of the *transmission efficiency* (losses between generator and pump motor, which can be important for submersible pumps), *motor efficiency* (conversion from electric to mechanical power), *shaft efficiency* (friction losses to bearings) and *bowl efficiency* (conversion of mechanical power to "hydraulic power", equal numerically to the volumetric flow rate through the pump multiplied by the total pump head).

Wellhead Power Plants

Several different types of wellhead plant were evaluated in the study (Pritchett, 1998):

- single-flash backpressure steam turbines,
- single-flash condensing steam turbines,
- double-flash steam turbines,
- binary plants, and
- flash-steam/binary hybrid designs.

Mathematical models were developed for each of these plants to facilitate the estimation of slim-hole generating capacity. Single-flash steam plants and binary plants are probably the most practical. Although the more complicated double-flash and hybrid design concepts offer slightly greater generating capacity for the same fluid supply, the improvement is likely to be offset by higher capital cost and increased maintenance. For remote sites, mechanical simplicity is an important priority.

Flash plants require a wellhead separator. For self-discharging wells, the pressure in the separator will be essentially the same as the flowing wellhead pressure. If a downhole pump is used to supply the flash plant, the pressurized wellhead liquid delivered by the pump must be expanded to separator pressure through an orifice. The separator provides a supply of saturated steam mixed with CO_2 gas to the turbine inlet (no liquid, no superheat) at separator pressure. Thus, plant inlet conditions are described by three parameters: steam mass flow rate, separator pressure, and CO_2 mass fraction in the steam.

Flash plant electrical capacity may be determined by (1) calculating the theoretical work rate of expansion from inlet conditions to outlet conditions for the turbine, and then (2) applying various efficiency factors and deducting parasitic loads. For a backpressure plant, the pressure at the turbine outlet is one atmosphere (0.101 MPa). For a condensing plant, expansion continues until the temperature reaches the value maintained in the condenser by the cooling system (taken as 39°C for these calculations). If CO_2 is negligible, the turbine outlet pressure will be only 0.007 Mpa for condensing plants, and will increase somewhat with increasing amounts of CO_2. Following Forsha (1994), the theoretical work rate of expansion is then modified to account for turbine efficiency (taken to be 0.75), gearbox efficiency (0.98) and generator efficiency (0.96). For condensing plants, the parasitic loads imposed by the liquid condensate pump, the NCG ("non-condensible gas") vacuum pump and the cooling tower fans must also be deducted. Results for negligible CO_2 are shown in Figure 3 in terms of net generating capacity as a function of separator pressure per unit inlet steam flow rate. Increasing CO_2 content will reduce power output somewhat by reducing work of expansion and by increasing NCG pump parasitic load.

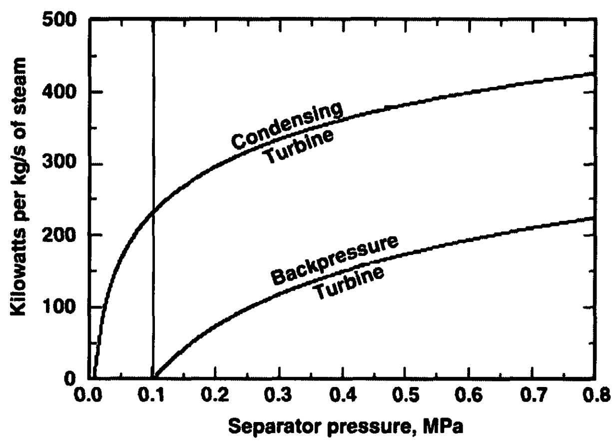

Figure 3. Single-flash power plant net capacity.

Double-flash steam plants are modeled similarly. The saturated liquid rejected by the primary wellhead HP ("high-pressure") separator is expanded into a "low-pressure" (LP) secondary separator, providing additional steam which is used to obtain additional turbine shaft power.

Unlike flash plants, binary plants operate using compressed brine provided by a downhole pump. The hot liquid passes through a heat exchanger, boiling a working fluid in a closed secondary fluid circuit. The cooled brine is reinjected. Mines (1997) devised a mathematical model for small binary plants suitable for off-grid projects, based on the following assumptions:

- The working fluid is a pure hydrocarbon: propane, isobutane, n-butane, isopentane, n-pentane, or hexane.
- The plant incorporates recuperation to enhance efficiency.
- Brine rejection temperatures must exceed the value required to avoid silica scaling in the heat exchanger:

$$T_{outlet}\,(°C) \geq 0.965 \times T_{inlet}\,(°C) - 117$$

Mines' model incorporates all pertinent losses and parasitic loads except that for the downhole pump itself, and was adopted without modification for the present study. Figure 4 shows model results for brine inlet temperatures between 80°C and 240°C for all six hydrocarbons considered. For a particular brine inlet temperature the hydrocarbon providing the highest electrical capacity was always selected:

< 109°C:	*hexane*
109°C to 164°C:	*propane*
164°C to 197°C:	*isobutane*
> 197°C:	*n-butane*

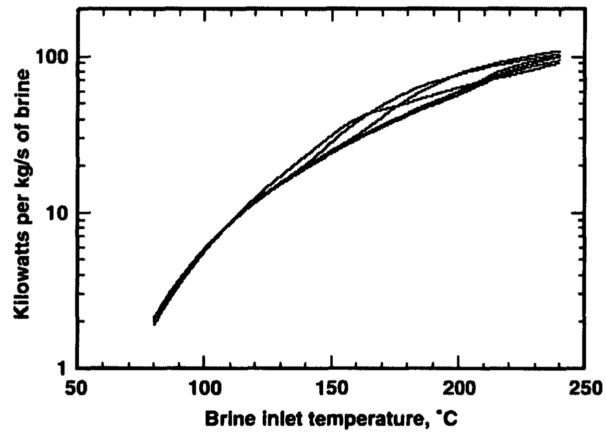

Figure 4. Electrical capacities of binary plants (no deduction for downhole pump).

so that the binary plant electrical capacity is given by the upper envelope of the curves in Figure 4, minus the power required by the downhole pump.

Flash-steam/binary hybrid plants consist of a single-flash steam plant (of either backpressure or condensing design – see above) combined with a binary plant which uses the hot liquid from the wellhead separator to power the heat exchanger. These plants may be modeled by simply combining the available power from both plant subsystems.

Optimizing for Maximum Electric Power

Three distinct situations arise when evaluating the maximum generating capacity of particular combinations of resource properties, well diameter and power plant design:

- *Case 1:* downhole pump but no wellhead separator.

- *Case 2:* downhole pump with a wellhead separator.
- *Case 3:* self-discharging well with wellhead separator.

The only "Case 1" situation of present interest is a wellhead binary plant powered by a pumped well. This case has no free parameters to optimize: the maximum wellhead liquid discharge rate is appraised (using a lineshaft or submersible pump as appropriate), and the electrical capacity is estimated using Mines' model (Figure 4), deducting the electrical requirements of the downhole pump.

The remaining cases all involve a wellhead separator, so that at least one free design parameter - the separator pressure - is available for performance optimization. For dual-flash plants, both the HP and the LP separator pressure must be optimized. The "Case 2" situations all involve downhole pumps, however, so that the flow rate and enthalpy of the liquid delivered to the wellhead depend only upon the downhole pump capacity and are independent of separator pressure. This simplifies the problem of optimization considerably. For a particular plant design (a single-flash condensing steam plant, for example), the optimum separator pressure (or pressures) will depend only upon wellhead enthalpy and CO_2 content. Thus, these optimum values may be calculated separately and stored for future use. Then, for a particular combination of well and reservoir properties, the optimum downhole pump design is found as in "Case 1", the gross electrical capacity of each of the candidate power plant designs is appraised using the stored values and the downhole pump parasitic load is deducted.

"Case 3", involving self-discharging wells, is the most difficult to optimize because the free wellhead separator pressure parameter influences not only the performance characteristics of the power plant but also the discharge characteristics (flow rate and discharge enthalpy) of the well itself. Consequently, optimization entails adjusting the properties of both parts of the system simultaneously, as indicated in Figure 5. Here, we consider the same well (150 mm ID, 600 m feedpoint depth, 100 m piezometric surface depth, 200°C reservoir temperature, no CO_2) as in Figure 2. Figure 5A shows how the steam flow rate from the separator will depend on separator (wellhead) pressure, according to the wellhead discharge characteristics shown in Figure 2. If this steam flow function is simply multiplied by the appropriate generating capacity function (Figure 3) for either a condensing or backpressure single-flash steam turbine, the relationships shown in Figure 5B are obtained. For either design, a particular separator pressure maximizes the electrical generating capacity. If the separator pressure is too high, output will decline because of inadequate steam output from the well (Figure 5A). If the pressure is too low, output decreases due to insufficient pressure difference between the turbine inlet and outlet (Figure 3). In general, the optimum separator pressure (and the maximum power available) depends on all of the parameter values (well diameter and feedpoint depth; reservoir pressure, temperature, CO_2 content and permeability; and which power plant design is employed). For single-flash condensing steam turbines, the optimum pressure depends mainly on reservoir temperature and is sub-atmospheric for reservoir temperatures below about 165°C.

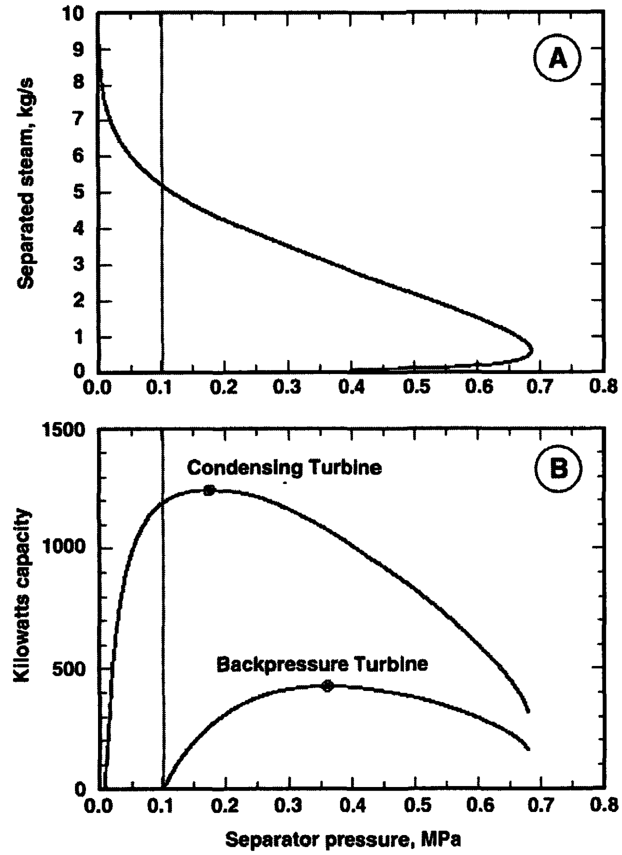

Figure 5. Optimization of single-flash plant designs for well described in Figure 2.

For any particular combination of the other parameters, the maximum electrical power available may be expressed by a curve relating electrical capacity to reservoir temperature. Figure 6 shows curves of this type for three popular systems (single-flash backpressure and condensing steam turbines on self-discharging wells, and a binary power plant fed by a downhole pump) for three different well diameters (300 mm ID standard well, and 150 and 75 mm ID slim holes). For 300 mm ID, the pumped-binary case employs a lineshaft pump; the 150 mm slim hole uses a submersible pump and the 75 mm slim hole is too small for application of a downhole pump. The results shown in Figure 6 (overleaf) are for negligible reservoir CO_2 and moderate reservoir permeability (40 kg/s per Mpa productivity index). The broad bands represent variations in well feedpoint depth (from 600 m to 1200 m) and in reservoir pressure (depth of piezometric surface from 50 to 150 m). Combining a single-flash sub-atmospheric condensing steam turbine with a pumped well is also a promising combination for low-temperature systems (not shown in Figure 6) which produces results comparable to (and sometimes better than) the binary system.

The results displayed in Figure 6 indicate that the backpressure steam turbine is substantially less capable than the other systems, but such plants are relatively inexpensive and robust. For high-temperature reservoirs, they can provide power in the 100-1000 kW range (shaded in Figure 6) using 150 mm ID slim holes. Clearly, drilling 300 mm ID standard

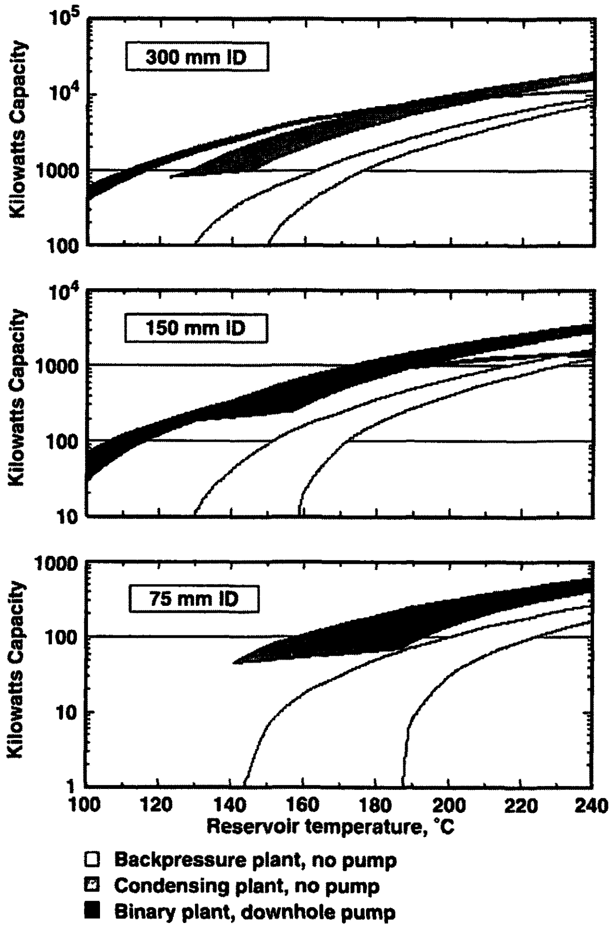

Figure 6. Electrical capacities of individual geothermal wells.

production wells is wasteful for projects in this size range. For standard (300 mm) wells, downhole pumps are helpful for reservoir temperatures below 200°C or so, but for 150 mm slim holes, self-discharging wells will usually outperform wells with downhole pumps if the reservoir temperature exceeds 160°.

Conclusions and Recommendations

Off-grid geothermal rural electrification projects in the 100-1000 kW range using slim holes are theoretically feasible. What is needed at this stage is practical information concerning costs and reliability of some of the proposed designs. For this purpose, a field-testing program is recommended.

Acknowledgements

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