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Cost of Geothermal Power and Factors that Affect It

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ABSTRACT

This paper presents an analysis of the sensitivity of the cost of geothermal power to: (a) capital cost; (b) operations-and-maintenance (O&M) cost; (c) make-up well drilling cost; (d) resource characteristics (well productivity and its rate of decline); (e) development and operational options (installed plant capacity, number of years of make-up well drilling, and project life); and (f) macro-economic climate (interest and inflation rates). The power cost here represents levelized cost (in US cents per kilowatt-hour) over the project life, the capital cost being amortized over 30 years; any royalties, tax burden, or tax credit are ignored. A range of development sizes, from 5 to 150 MW, with 50 MW as the base case, is considered. The economy of scale in both capital cost and O&M cost, as well as the higher productivity decline rate due to increased installed capacity, are taken into account. The capital cost does not include transmission line cost or any unusually site-specific costs of regulatory compliance or environmental impact mitigation.

Power cost is sharply reduced if full generation capacity is maintained, by drilling make-up wells, for at least the first 10 years or so following plant start-up; however, continuing make-up well drilling beyond about 20 years does not reduce power cost any further. The minimum achievable power cost is insensitive to plant capacity; it is on the order of 3.4US¢ / kWh. There are significant opportunities to reduce power cost as site-specific experience is gained in resource management and power plant operation throughout the project life. Power cost is most sensitive to unit O&M cost followed by unit capital cost, interest rate and inflation rate in the decreasing order of sensitivity; it is relatively insensitive to well productivity, drilling cost per well and well productivity decline rate. The macro-economic climate has relatively minor impact on power cost. Operating small power plants beyond their typical amortization period of 30 years can substantially reduce power cost; this reduction is insignificant for plants of 50 MW or larger capacity. Power cost does not decline significantly with increasing plant capacity except in the unlikely situation of well productivity decline being insensitive to plant capacity. In the unusual situation of an absence of economy of scale, power cost increases with plant capacity, the minimum achievable level still being 3.4US¢ / kWh. In the very unlikely situation of both well productivity decline as well as unit capital and O&M costs being insensitive to plant capacity, the minimum achievable power cost would be on the order of 3.6US¢ / kWh. For a 50 MW power plant today, the levelized power cost would be in the range of 3.6 to 4.1 US¢/kWh.

1. INTRODUCTION

Both capital cost and operations-and-maintenance ("O&M") costs of geothermal power have declined substantially over the last decade (see, for example, Entingh and McVeigh, 2003). In light of this development, it is worthwhile assessing the overall cost of geothermal power today. The power cost considered here is "levelized" cost in cents per kilowatt-hour (US¢/kWh) over the project life, the initial capital cost being amortized over a period of 30 years; make-up well drilling cost is not capitalized and is considered an operating expense. The capital cost includes the cost of money (that is, the cumulative present value of all future interest payments) but does not include any transmission line cost or any unusually site-specific costs of regulatory compliance or environmental impact mitigation.

This paper considers power cost rather than power price or project profitability because, unlike price or profitability, cost is substantially independent of the corporate culture of the developer and operator, financing mechanism, local market forces and government policies. Furthermore, cost calculations in this paper ignore any royalty burden, tax liability or tax credit. Therefore, although the values of economic parameters assumed in this paper reflect the present setting in the United States, the conclusions arrived at should be applicable at least qualitatively, if not quantitatively, to geothermal power projects worldwide. In the currently fashionable debate over the relative virtues of various forms of renewable energy, power cost is an objective criterion that should favor geothermal; yet there is considerable difference of opinion as to what it truly is and can be. Hence the justification for this analysis.

The analysis considers a power capacity range of 5 to 150 MW with 50 MW as the "base case." Power cost consist of three components: (a) capital cost component (including cost of money), (b) O&M cost component (not counting debt service, which is included under the capital cost component), and (c) make-up well drilling cost component, as described in the Appendix.

2. FACTORS THAT AFFECT GEOTHERMAL POWER COST

These factors can be grouped into four categories: (a) economy of scale, (b) well productivity characteristics, (c) development and operational options, and (d) macro-economic climate. In general, economy of scale allows both unit capital cost (in US dollars per kW installed) and unit O&M cost (in US¢/kWh) to decline with increasing installed capacity. Based on the data presented by Entingh and McVeigh (2003), the unit capital cost is estimated to vary from US$1,600/kW to US$2,500/kW depending on project size and other project-specific criteria. For the smallest project size of 5 MW considered here, we have assumed a unit capital cost of US$2,500/kW and for the largest considered project size of 150 MW a cost of US$1,600/kW; however, based on GeothermEx's recent experience with projects in the U.S., we believe Entingh and McVeigh (2003)'s costs are slight underestimates. We have further made the permissive assumption that within the above range of values, unit capital cost declines exponentially with plant capacity. This assumption leads to the following correlation between unit capital cost in US$/kW ($c_d$) and plant capacity in kW (P):

$$c_d = 2500e^{-0.003(P-5)}. \quad (1)$$

For the 50 MW base case the unit capital cost is estimated from (1) at US$2,184/kW; as stated before, this estimate following the work of Entingh and McVeigh (2003) is somewhat low. Based on GeothermEx's experience, we believe the representative unit O&M cost approximately ranges from 2.0US¢/kWh for a 5 MW plant to 1.4US¢/kWh for a 150 MW plant. Assuming an exponential decline in unit O&M cost in US¢/kWh (c_o) with plant capacity in kW (P), we get:

$$c_o = 2.0e^{-0.0025(P-5)}. \quad (2)$$

For the 50 MW base case the unit O&M cost is estimated from (2) at 1.79US¢/kWh.

Well productivity characteristics affect geothermal power cost in mainly two ways:

a) if well productivity is higher, fewer wells are needed to supply a plant, thus reducing power cost; and

b) a higher rate of decline in well productivity with time calls for more make-up well drilling, and therefore, leads to higher power cost.

For the purposes of this paper, an average initial productivity of 5 MW per well was assumed; this is a typical value. Geothermal wells generally undergo "harmonic" decline in well productivity with time (Sanyal, *et al*, 1989):

$$W = \frac{W_i}{1 + D_i t}, \quad (3)$$

where W_i is initial productivity, D_i is initial annual decline rate in productivity and W is productivity in year t. The harmonic decline trend implies a decline rate that slows down with time, the annual decline rate (D) in productivity in year t being given by (Sanyal, et al, 1989):

$$D = \frac{D_i}{1 + D_i t} \quad (4)$$

If the total production rate from a field is small enough to be entirely compensated by natural recharge or if only a small fraction of the productive reservoir is being exploited, the decline rate in well productivity would be insensitive to increases in plant capacity. These situations are much less common. In most cases decline rate increases with increasing installed capacity. This sensitivity of productivity decline to installed capacity is too site-specific to be quantified by a generally-applicable correlation. Nevertheless, Sanyal, *et al* (2000) attempted an approximate formulation:

$$D_i' = \left(\frac{W_i'}{W_i}\right)\left(\frac{\ln W_i'}{\ln W_i}\right) D_i, \quad (5)$$

where D_i is initial annual harmonic decline rate when total production rate is W_i and D_i' is initial annual harmonic decline rate when total production rate is changed to W_i'. Assuming a typical initial harmonic decline rate of 5% per year for the 50 MW base case, the initial annual harmonic decline rate for any other plant capacity was estimated from (5).

There are certain resource development and operational options that affect power cost. The developer of a geothermal project has the option to size the power plant while the operator of the project has the option to either allow generation to decline with time or to maintain generation by make-up well drilling; the operator can also run the plant beyond its amortized life. The sensitivity of power cost to these intertwined options has been studied in this paper. The resource development option has been considered by varying the plant capacity within the range of 5 to 150 MW. The operational option has been considered by assuming make-up well drilling for various periods of time following plant start-up, and scenarios of plant operation both up to and beyond the amortization period.

While the unit capital cost for a given plant capacity, as given by (1), includes initial drilling cost, the unit O&M cost given by (2) does not include make-up well drilling cost. In order to estimate the make-up well drilling cost as a function of time, it is necessary to estimate first the initial number of wells required for a given plant capacity. This estimate was based on a typical initial productivity of 5 MW per well plus the customary need for at least one stand-by well and a minimum of 10% reserve production capacity at all times. With the above assumptions it follows that the installed plant capacity can be maintained without any make-up well drilling for up to t_c years following plant start-up, as given by:

$$t_c = \frac{1}{D_i}\left[\frac{W_i N_{wi}}{(1 + r/100)P} - 1\right], \quad (6)$$

where D_i is initial annual harmonic decline rate, W_i is initial productivity per well (MW), N_{wi} is initial number of wells (including at least one stand-by well), P is plant capacity (MW), and r is minimum production capacity reserve required (%).

3. CALCULATION OF LEVELIZED POWER COST

Figure 1 shows the schematic generation and make-up well drilling histories of a typical power project. Generation can be maintained without make-up well drilling up to year t_c, as given by (6). Then generation is maintained by make-up well drilling up to year t_d in response to decline in well productivity according to (3), the initial annual harmonic decline rate being given by (5). After year t_d, no make-up well is drilled and generation is allowed to decline as per (3) and (5).

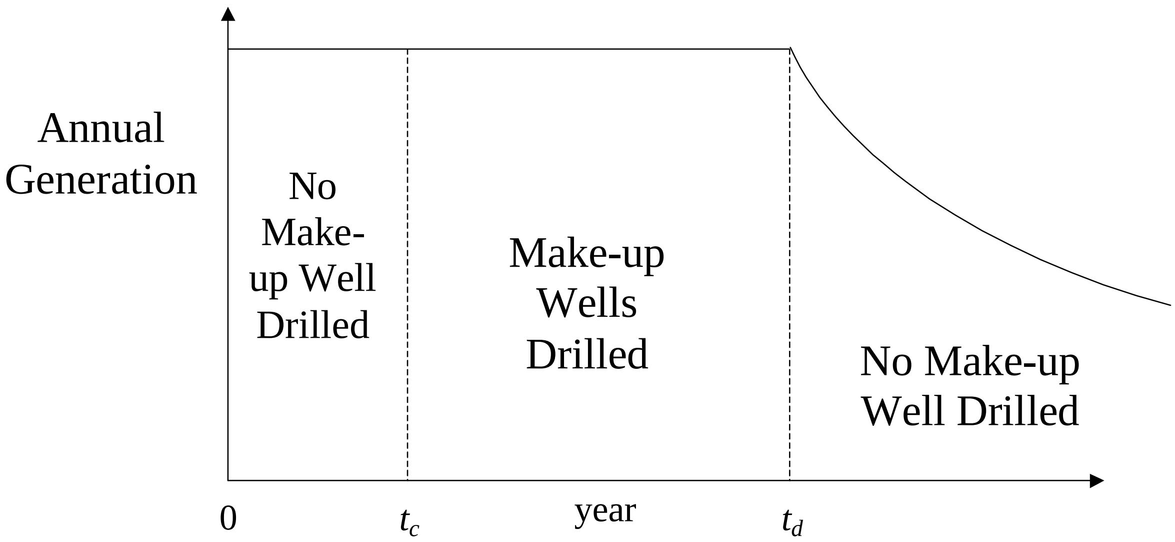

Figure 1. Schematic Generation and Make-up Well Drilling Histories of a Project

Given the generation and make-up well drilling histories represented in Figure 1, the levelized cost of geothermal power $(\bar{c})$ in US¢/kWh is given by (see Appendix):

$$\bar{c} = \frac{100D(t_d)}{G\{D(t_d)t_d + \ln[1 + D(t_d)(n - t_d)]\}} \cdot \left\{\frac{iC(1+i)^n}{(1+i)^n - 1}\right\}\left\{\frac{(1+I)^n - 1}{I(1+I)^{n-1}}\right\} + c_{ov} + \left(\frac{t_d}{n}\right)c_{ofi} + \frac{c_{ofi}}{n}\left\{(n - t_d) + \frac{D(t_d)}{2}(n - t_d)^2\right\} + \frac{100C_{wi}N_{wi}D(t_d)D(t_c)(t_d - t_c)}{G\{D(t_d)t_d + \ln[1 + D(t_d)(n - t_d)]\}}, \quad (7)$$

where $D(t)$ is annual productivity decline rate in year t; G is initial annual generation (kWh); N is power plant life (assumed to be 30 years in base case); C is total capital cost, that is, $c_d \cdot P$ (US$); c_o is unit annual O&M cost (US¢/kWh); i is annual interest rate (assumed to be 7% in base case); I is annual inflation rate (assumed to be 3% in base case); c_{ofi} is fixed portion of the annual O&M cost at plant start-up divided by initial annual generation (US¢/kWh); c_{ov} is variable portion of the annual O&M cost divided by annual generation (US¢/kWh); N_{wi} is number of initial production wells; and C_{wi} is drilling cost per initial production well (assumed to be $2 million in the base case).

Capital cost includes exploration cost, power plant cost, gathering and injection system cost and cost of capital. Annual O&M cost includes personnel cost, general and administrative cost, insurance cost, supplies / consumables / engineering and laboratory services cost, wellfield maintenance cost, generator and turbine maintenance cost and other equipment and maintenance cost.

The variable portion of the annual O&M cost represents costs that vary with the level of generation, such as, costs of supplies, consumables, etc, which remain proportional to generation; this cost divided by annual generation gives c_{ov}. The fixed portion of the annual O&M cost represents costs that are independent of the generation level; these include costs of personnel, administration, insurance, wellfield maintenance, generator and turbine maintenance, other equipment maintenance, etc., which may not decline in response to any decline in generation. This fixed annual cost divided by annual generation gives c_{of}. For the purposes of this paper 20% of the annual O&M cost was assumed to vary with generation at plant start-up; however, results are found to be relatively insensitive to the fraction of O&M cost that is variable. As generation declines, c_{ov} remains constant but c_{of} increases from its initial value of c_{ofi}.

A typical plant capacity factor of 90% was assumed in estimating annual generation. In (7), the total capital cost (C) is assumed to be amortized over the plant life of n years at an interest rate i (annual compounding). The calculated power costs in future years are discounted for inflation to arrive at a levelized power cost in present dollars $(\bar{c})$.

4. RESULTS

It should be noted that if there were no economy of scale in capital and O&M costs (that is, a capital cost of US$2,184/kW and an O&M cost of 1.79US¢/kWh, as in the base case) and if productivity decline rate were insensitive to installed capacity (remaining at 5% initial annual harmonic rate as in the base case), levelized power cost from (7) would be 3.6US¢/kWh irrespective of plant capacity. Table 1 lists all parameters for the range of development scenarios analyzed, assuming the economy of scale in capital and O&M costs as well as the sensitivity of productivity decline to plant capacity.

Table 1. Development Scenarios Analyzed

Plant Capacity (MW)	Unit Capital Cost (US$/kW)	Total Capital Cost (Million US$)	Unit O&M Cost (US¢/kWh)	Initial Harmonic Decline Rate (%)	No. of Initial Production Wells	Years before Make-up Well Drilling is Required (t_c)
5	2,500	12.5	2.0	0.2	2	>30
10	2,463	24.6	1.98	0.6	3	>30
20	2,390	47.8	1.93	1.5	5	9
30	2,319	69.6	1.88	2.6	7	2
50	2,184	109.2	1.79	5.0	11	0
75	2,025	152.0	1.68	8.3	17	0
100	1,880	188.0	1.58	11.8	22	0
125	1,744	218.0	1.48	15.4	28	0
150	1,618	242.7	1.39	19.2	33	0

Figure 2 shows the calculated power cost in US¢/kWh for various levels of installed plant capacity as a function of t_d (that is, the number of years of make-up well drilling undertaken to maintain plant capacity). This figure takes into account the economy of scale as reflected in (1) and (2), as well as acceleration in well productivity decline, as given by (5), with increased installed capacity. Figure 2 indicates that power cost declines with the number of years of make-up well drilling, the decline rate being steeper for a higher plant capacity. Figure 2 also indicates that if make-up well drilling is discontinued too early (prior to about 10 years), power cost would be higher for a larger plant. This figure also shows that for any plant capacity, a relatively minor reduction in power cost is achieved by continuing make-up well drilling after this period, and continuing make-up well drilling beyond about 20 years may actually increase power cost. Therefore, there is little reason to continue make-up well drilling beyond about 20 years unless the power sales contract imposes significant penalties for any shortfall in plant capacity.

Figure 3 shows the minimum achievable power cost for various plant capacities as read from Figure 2. This figure shows that the minimum achievable power cost is rather insensitive to plant capacity; it varies from 3.7US¢/kWh for a 10 MW plant to 3.4US¢/kWh for a 150 MW plant, a 7.6% decline in power cost for a 1400% increase in power capacity. Irrespective of the plant capacity and the number of years of make-up well drilling, power cost today cannot be lowered significantly below 3.4US¢/kWh. Figure 4 shows the three components of power cost (capital, O&M, and make-up well drilling) as functions of plant capacity assuming make-up well drilling to be discontinued after 20 years. This figure shows that the capital cost component is approximately equal to the O&M cost component for all plant capacities while the make-up well drilling component assumes greater significance with increasing plant capacity (except for very small capacities). Furthermore, the sum of O&M and make-up well drilling components constitutes the major part of power cost. Capital expenditure is incurred in the first few years of a project, when site-specific knowledge of the resource is still limited; therefore, adequate optimization of capital investment can be a challenge. After plant start-up little can be done to reduce the capital cost component of power cost, except perhaps refinancing the debt should the interest rate decline. On the other hand, O&M and make-up well drilling costs, being incurred gradually as production continues, should reduce with time due to the "learning curve" effect. As more understanding of the resource characteristics and reservoir performance is gained with operation, O&M and make-up well drilling costs can be reduced, lowering power cost.

Figure 5 is a plot of power cost versus percent deviation in the values of the various independent variables from their base case (50 MW) values. In this figure, a steeper curve through the base case point implies a higher sensitivity of power cost to the variable represented by the curve. Figure 5 shows that unit O&M cost and unit capital cost have the highest impact on power cost; these two variables are also subject to economy of scale. On the other hand, power cost is relatively insensitive to resource-related variables (such as well productivity, drilling cost per well and productivity decline rate). Figure 5 indicates a levelized power cost of 3.6US¢/kWh for a 50 MW plant. However, it should be noted that recent experience of GeothermEx indicates that the estimates of capital cost in the U.S. based on Entingh and McVeigh (2003) is somewhat low. For the base case, the capital cost in the U.S. may be as much as 30% higher than US$2,184/kW. Therefore, Figure 5 shows that the levelized power cost for a 50 MW plant in the U.S. may be as high as 4.1US¢/kWh.

Interestingly, power cost is only modestly sensitive to macro-economic variables (interest and inflation rates), because interest and inflation rates affect power cost by about the same magnitude but in opposite directions (Figure 5). Figures 6 shows power cost versus plant capacity for several diverse micro-economic situations: (1) a hyper-inflationary environment, (2) a high inflationary environment, (3) the current economic environment in the U.S., and (4) a deflationary environment; appropriate interest rates (*i*) and inflation rates (*I*) assumed for the various cases are shown on the figure. Figure 6 implies that, in relative terms, the sensitivity of power cost to the macro-economic climate is not significant. For example, the variation in power cost over the capacity range of 5 to 150 MW is of similar magnitude as the variation in power cost in the base case over the extreme range of macro-economic climates considered.

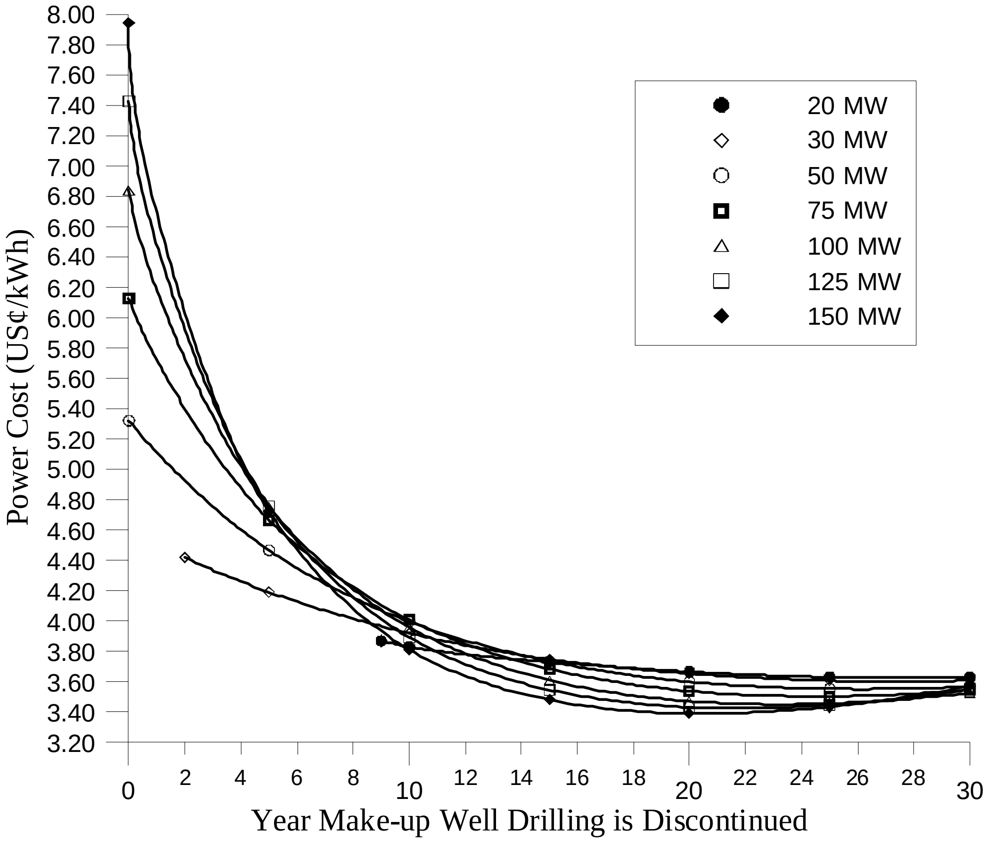

Figure 2. Power Cost versus the Year Make-up Well Drilling is Discontinued

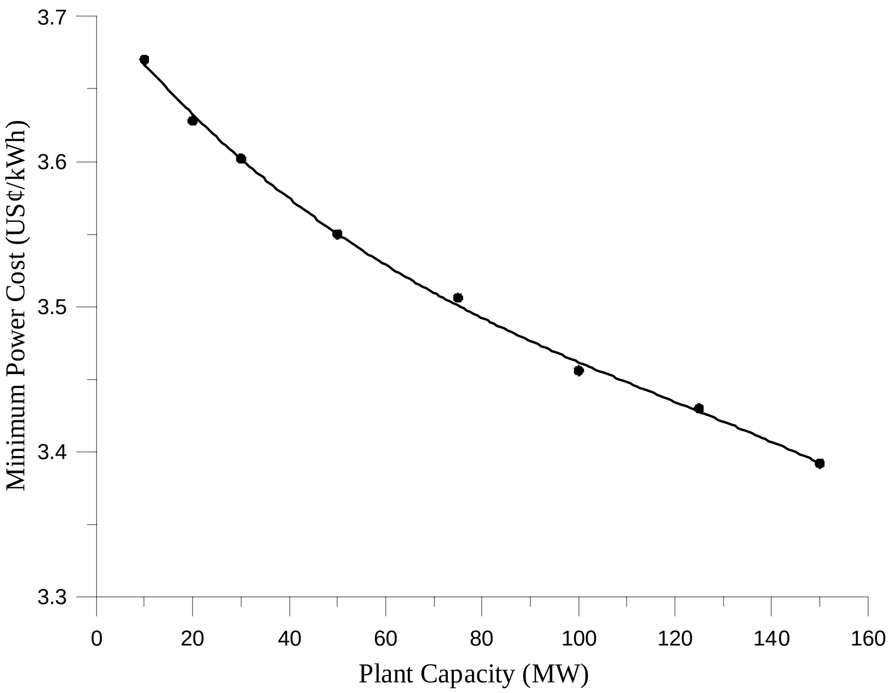

Figure 3. Minimum Power Cost versus Plant Capacity

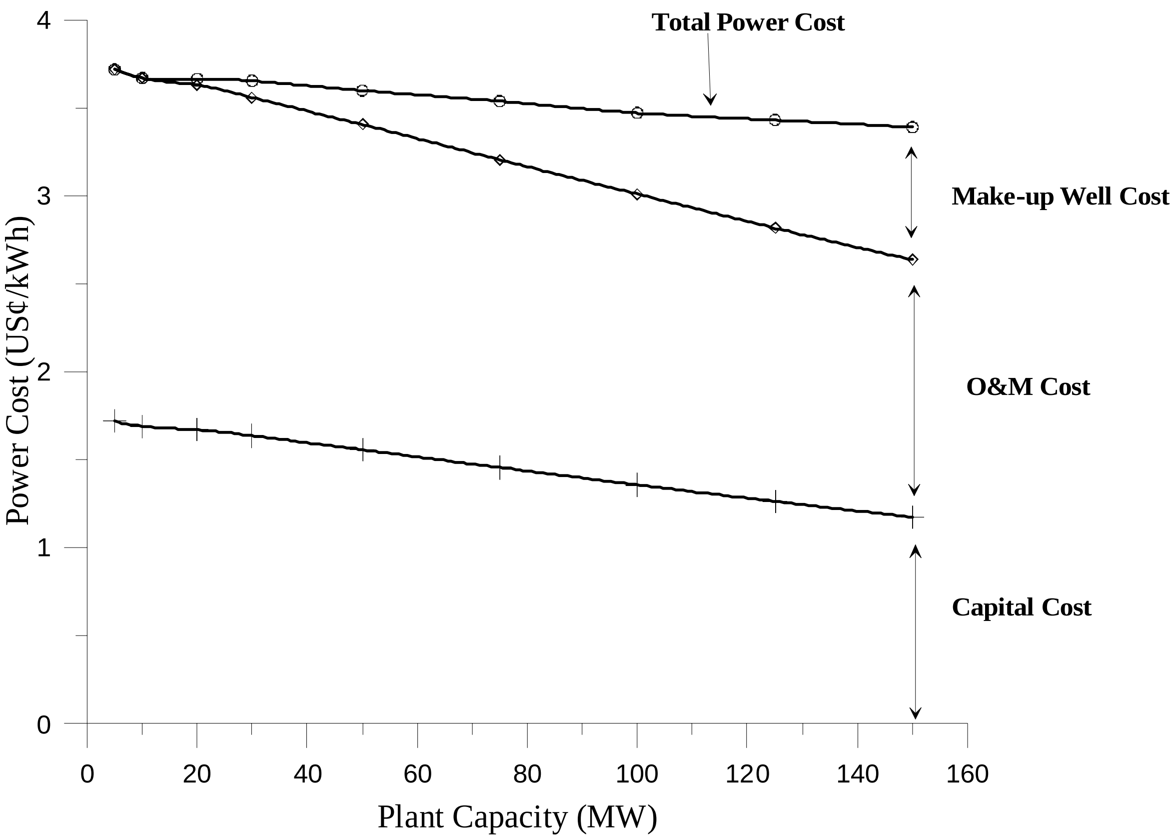

Figure 4. Power Cost Components versus Plant Capacity (Assuming 20 Years of Make-up Well Drilling)

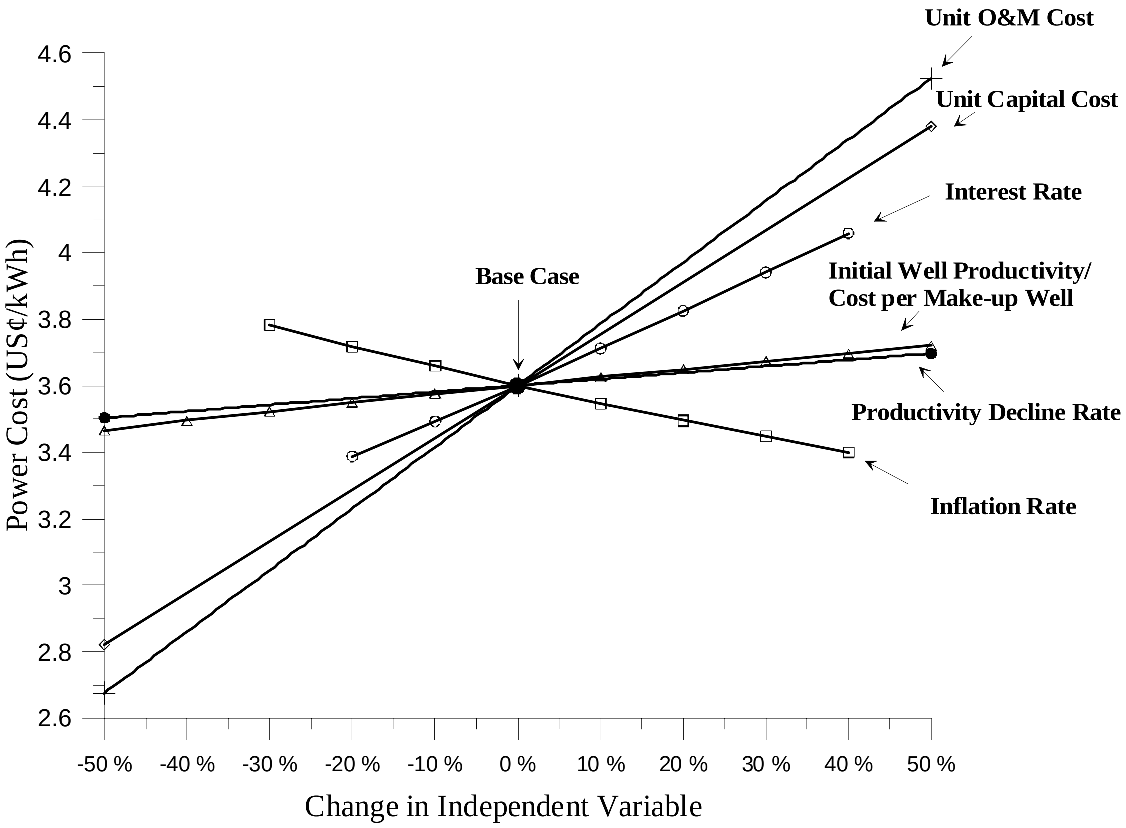

Figure 5. Sensitivity of Base Case Power Cost to Changes in Independent Variables

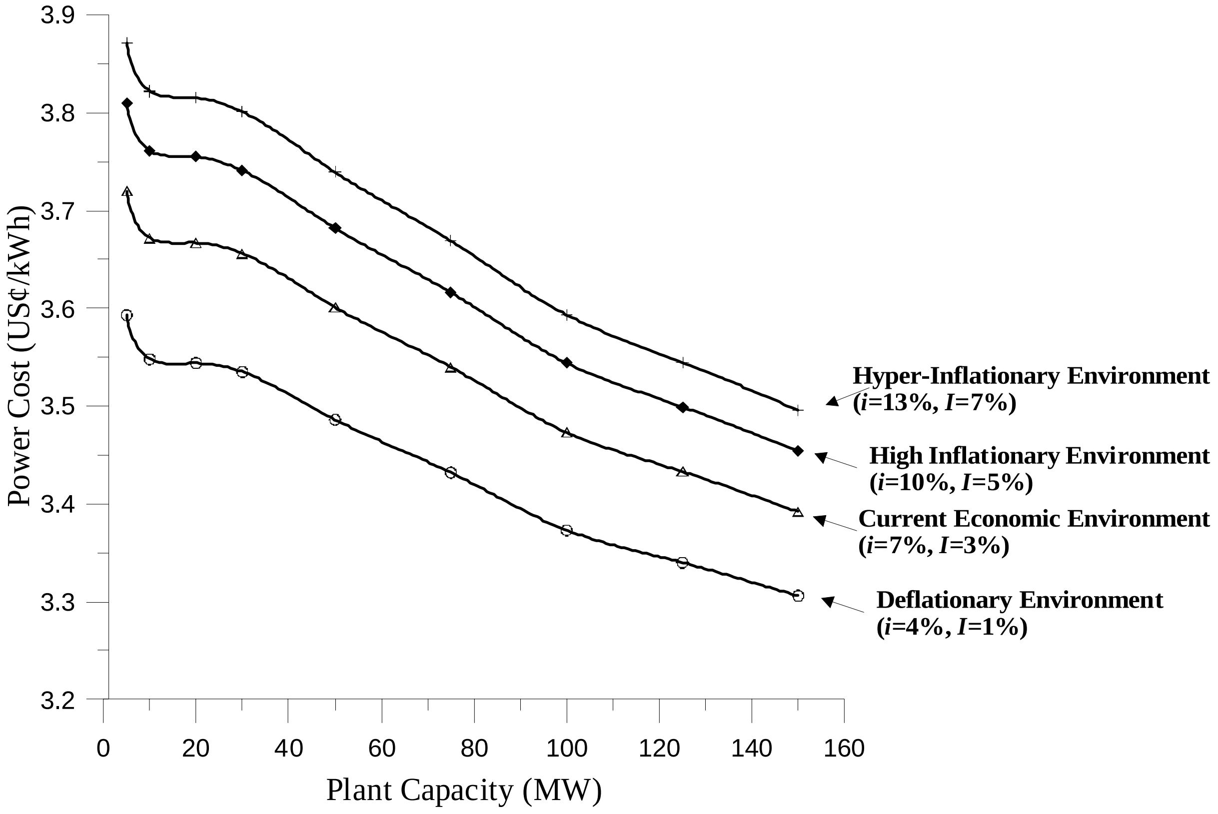

Figure 6. Power Cost versus Plant Capacity under Various Macro-economic Conditions (For 20 Years of Make-up Well Drilling)

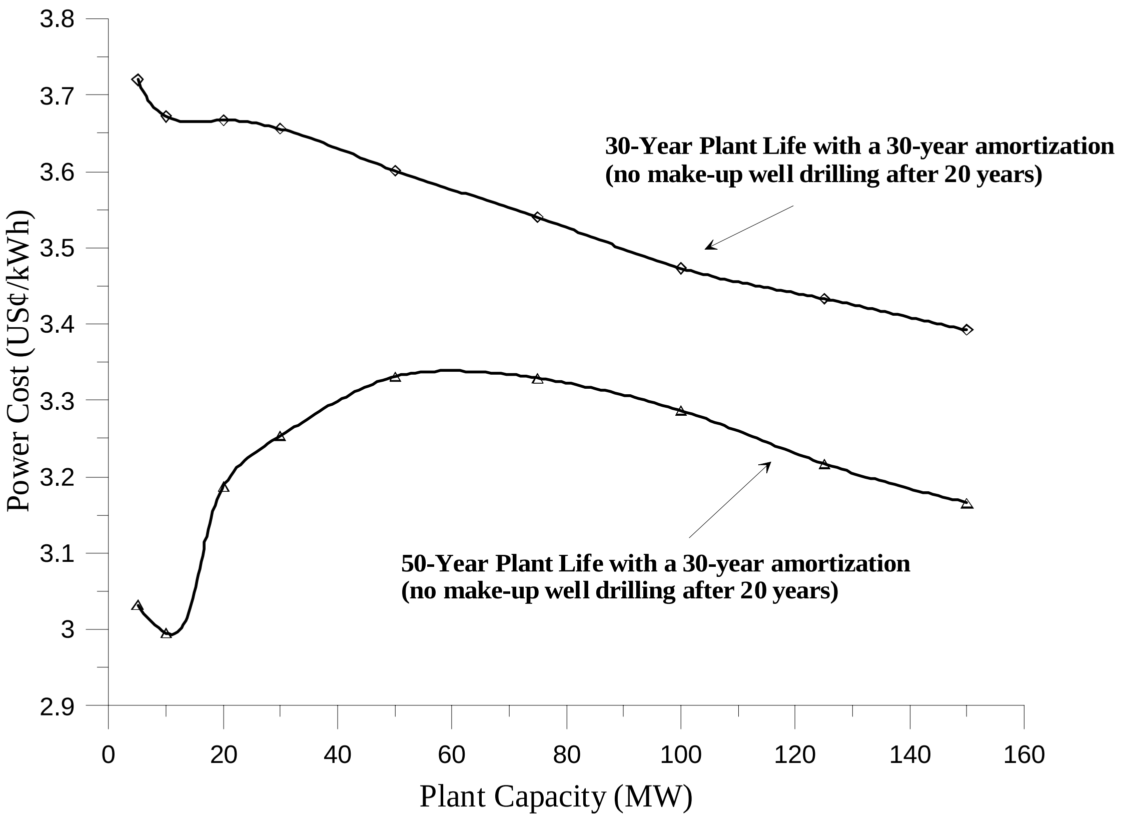

Figure 7. Effect of Plant Life on Power Cost (20 Years of Make-up Well Drilling)

History of operation of geothermal power plants in Italy, New Zealand, El Salvador, Mexico and U.S., where some plants have now operated for more than 30 years, indicates that it is possible to continue operating a geothermal plant beyond its typical amortization period of 25 to 30 years. Can power cost be reduced if a geothermal plant were amortized for 30 years but operated for a longer period? Figure 7 compares power cost versus plant capacity as shown before (for 30 years' operation) and as calculated for a 50-year operating period, the initial capital cost still being amortized over 30 years. Figure 7 shows that for smaller plants, cost may be reduced significantly, by as much as 20% for plants of 10 MW or smaller capacity. For plants larger than about 50 MW, this reduction in power cost is not significant, particularly considering the additional risk of operating an aging power plant and pipelines, and possibly deteriorating wells.

The above analysis takes into account the usual acceleration in well productivity decline due to increases in plant capacity. How would the results change in the unusual case of well productivity being insensitive to installed plant capacity? Figure 8 compares levelized power cost as a function of plant capacity, as calculated before, with the case of a constant initial annual harmonic decline rate of 5% irrespective of capacity. Figure 8 shows that if productivity decline rate were insensitive to plant capacity, power cost would decline with plant capacity much more rapidly than in the usual case, the minimum power cost being only 2.8US¢/kWh (for a 150 MW plant). However, a stand-alone project of a capacity larger than 100 MW is a rarity in the geothermal industry. The existing fields with a generation level greater than 100 MW typically rely on multiple, independent units of up to 100 MW each; as such, the economy of scale enjoyed by these projects would amount to that for a capacity of 100 MW or less. Therefore, if well productivity were insensitive to plant capacity, a power cost of less than 3.2US¢/kWh (estimated for a 100 MW plant) is unlikely to be realized.

Finally, how would the results change if economy of scale in capital and O&M costs were negligible? One such conceivable situation could be the installation of multiple, modular and infrastructurally-independent power plants in the same field. Figure 9 presents power cost versus the number of years of make-up well drilling for various plant capacities ignoring economy of scale. The results in this figure assume that unit capital and O&M costs remain the same as in the base case irrespective of installed capacity, but productivity decline still increases with installed capacity as given by (5). Figure 9 indicates that if economy of scale were negligible, power price would increase with installed capacity no matter how long one continues make-up well drilling, and power price would be consistently higher than in the usual case with economy of scale. The minimum achievable power cost in this case is still on the order of 3.4US¢/kWh (estimated for a 20 MW plant).

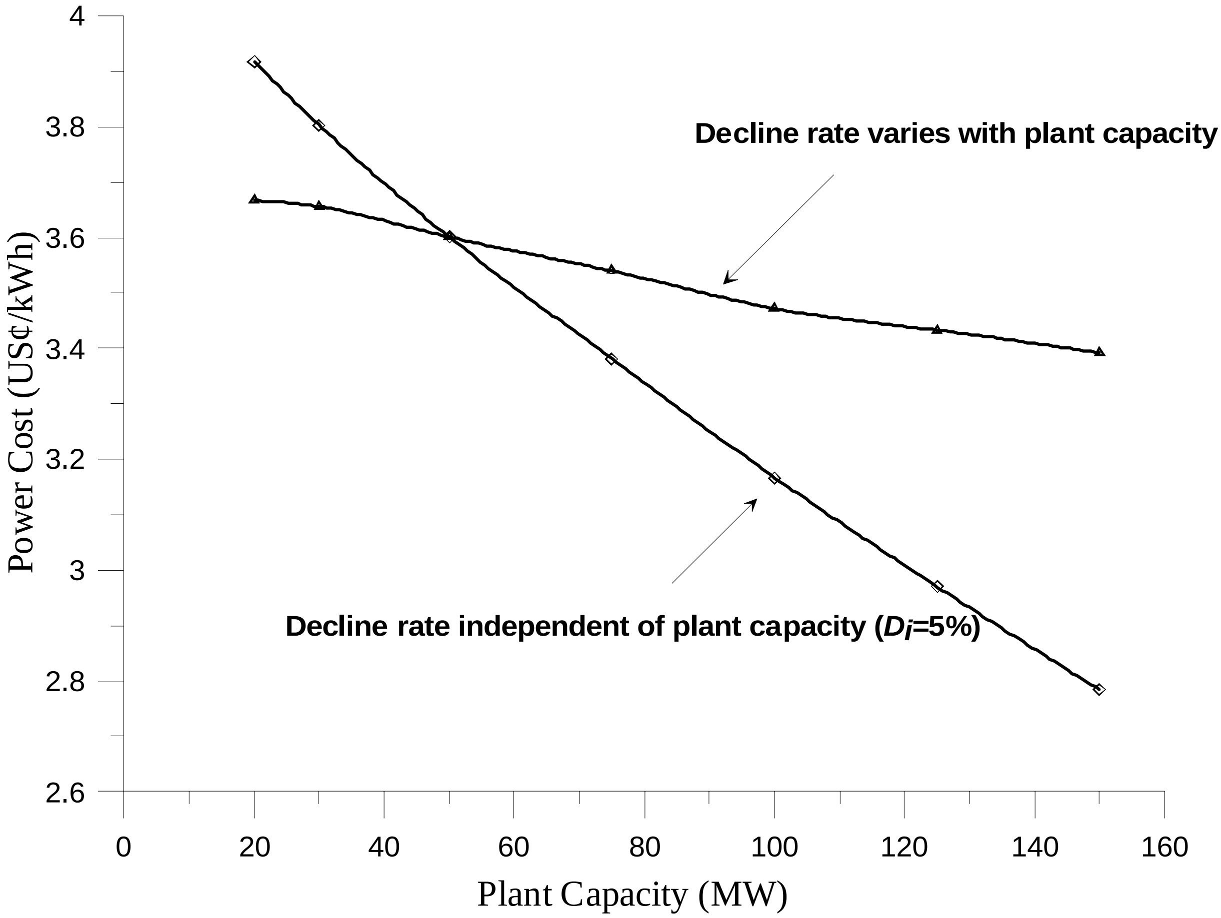

Figure 8. Power Cost versus Plant Capacity (For 20 Years of Make-up Well Drilling)

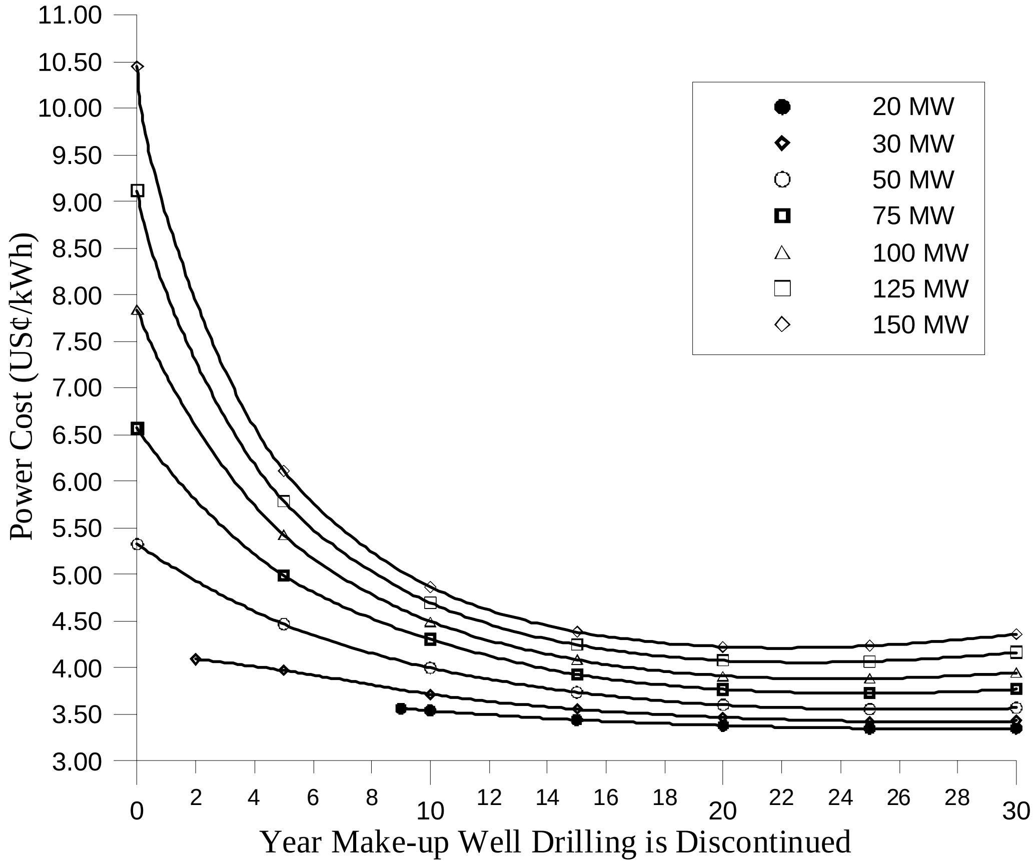

Figure 9. Power Cost versus the Year Make-up Well Drilling is Discontinued ("No Economy of Scale" Case)

5. CONCLUSIONS

1. Power cost is sharply reduced by maintaining full generation capacity, by drilling make-up wells, for at least the first 10 years or so following plant start-up; continuing make-up well drilling beyond 20 years does not reduce power cost.

2. The minimum achievable power cost is insensitive to plant capacity; it is on the order of 3.4US¢/kWh. There are significant opportunities to reduce power cost as site-specific experience is gained in resource management and power plant operation throughout the project life.

3. The levelized cost of power from a 50 MW plant is in the range of 3.6 to 4.1 US¢/kWh.

4. Power cost is most sensitive to unit O&M cost followed by unit capital cost, interest rate and inflation rate in the decreasing order of sensitivity; it is relatively insensitive to well productivity, drilling cost per well, well productivity decline rate and the macro-economic climate.

5. Operating small power plants beyond their typical amortization period of 30 years can significantly reduce power cost; this reduction is not significant for plants of 50 MW or larger capacity.

6. The minimum achievable power cost does not decline significantly with increasing plant capacity except in the unlikely situation of well productivity decline being insensitive to capacity, when it may be as low as 3.2US¢/kWh. In the unusual situation of an absence of economy of scale, power cost increases with plant capacity, the minimum achievable level being 3.4US¢/kWh. In the very unlikely situation of both well productivity decline as well as unit capital and O&M costs being insensitive to plant capacity, the minimum achievable power cost would be on the order of 3.6US¢/kWh.

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APPENDIX: CALCULATION OF LEVELIZED POWER COST

Total generation over the plant life ($\sum G$) is:

$$\sum G = G t_d + G\int_{t_d}^{n} \frac{dt}{[1+D(t_d)(t-t_d)]}$$

$$= G\left\{t_d + \frac{\ln[1+D(t_d)(n-t_d)]}{D(t_d)}\right\},\ D(t_d) \neq 0 \quad \text{(A-1)}$$

Assuming annual compounding, annual payment (USA) to amortize the total capital cost (USC) for n years is given by:

$$A = \frac{iC(1+i)^n}{(1+i)^n - 1} \quad \text{(A-2)}$$

Inflation-discounted sum ($\sum A_i$) of n annual payments of USA per year is given by:

$$\sum A_i = \sum_{t=0}^{n-1} \frac{A}{(1+I)^t}$$

$$= \left\{\frac{iC(1+i)^n}{(1+i)^n - 1}\right\} \cdot \left\{\frac{(1+I)^n - 1}{I(1+I)^{n-1}}\right\} \quad \text{(A-3)}$$

The capital cost component of levelized power cost $(\bar{c}_{CAP})$ in US¢/kWh is given from (A-1) and (A-3).

$$(\bar{c}_{CAP}) = \frac{\sum A_i}{\sum G} \cdot 100$$

$$= \frac{100D(t_d)}{G\{D(t_d)t_d + \ln[1+D(t_d)(n-t_d)]\}}$$

$$\cdot \left\{\frac{iC(1+i)^n}{(1+i)^n - 1}\right\}\left\{\frac{(1+I)^n - 1}{I(1+I)^{n-1}}\right\} \quad \text{(A-4)}$$

Up to time t_d, generation remains constant and so does the uninflated value of the unit O&M cost (c_o). As generation declines after time t_d, c_{ov} (expressed in US¢/kWh) remains constant but c_{of} (expressed in US¢/kWh) increases as generation declines from G to G' as :

$$c_{of} = \frac{c_{ofi} G}{G'} . \quad \text{(A-5)}$$

Assuming harmonic decline, from (3),

$$c_{of} = c_{ofi}[1+D(t_d)(t-t_d)] \quad \text{(A-6)}$$

Therefore, the O&M cost component of levelized power cost $(\bar{c}_{O\&M})$ in US¢/kWh, ignoring inflation, is given by:

$$\bar{c}_{O\&M} = \frac{1}{n}\left[n c_{ov} + t_d \cdot c_{ofi} + c_{ofi}\int_{t_d}^{n}\{1+D(t_d)(t-t_d)\}dt\right]$$

$$= c_{ov} + \frac{t_d}{n}\cdot c_{ofi} + \frac{c_{ofi}}{n}\left\{(n-t_d) + \frac{D(t_d)(n-t_d)^2}{2}\right\} \quad \text{(A-7)}$$

No make-up well is drilled up to year t_c; therefore, the total number of production wells servicing the plant is still N_{wi}. After time t_c, make-up wells are drilled to maintain generation. The total number of production wells (N_{td}) servicing the plant at time t_d is given by:

$$N_{td} = N_{wi}[1+D(t_c)(t_d-t_c)] \quad \text{(A-8)}$$

The total number of make-up wells drilled (ΔN) between time t_c and t_d is, therefore,

$$\Delta N = N_{wi} D(t_c)(t_d - t_c) \quad \text{(A-9)}$$

The total cost of make-up well drilling over the plant life in dollars is (ΔN) (C_{wi}) for the total lifetime generation given by (A-1). The make-up well cost component of levelized power cost $(\bar{c}_{MW})$ in US¢/kWh, ignoring inflation, is then given by:

$$\bar{c}_{MW} = \frac{100 C_{wi} N_{wi} D(t_d) D(t_c)(t_d - t_c)}{G\{D(t_d)t_d + \ln[1+D(t_d)(n-t_d)]\}},\ D(t_d) \neq 0. \quad \text{(A-10)}$$

Finally, levelized power cost $(\bar{c})$ is given by:

$$\bar{c} = \bar{c}_{CAP} + \bar{c}_{O\&M} + \bar{c}_{MW} \quad \text{(A-11)}$$

Using (A-4), (A-7) and (A-10) in (A-11), we get (7).