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Investment cost for geothermal power plants

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Abstract

Stepwise development strategy is considered a suitable method for securing a cost-effective way for the development of geothermal power plants. This strategy has been in use in Iceland for the last decade. Geothermal high-temperature fields are developed in steps of 20–30 MW. About 6 years are required for each step in the development. Parallel development of several fields in a country might be preferable, especially when a rapid increase of the generation capacity is required in that country. The capacity factor of geothermal power plants depends on the mix of power plants serving the electricity grid. Where geothermal power plants can be operated as base load, the capacity factor is usually in excess of 0.9. The investment cost of geothermal power plants is divided into the cost of surface equipment and activities and the cost of subsurface investment. The surface costs include the cost of surface exploration, and the plant and steam-gathering system, while the cost of subsurface investment is that of drilling. Surface equipment costs can be estimated with the same accuracy as other construction works at the surface (buildings, roads, bridges), whereas higher uncertainty might be associated with the cost of drilling. Analyses of the surface costs of five power plants in Iceland show that the investment cost of the surface equipment is linear with size, in the range 20–60 MW. Surface costs were found to be about 1000 USD/kW with a relative error of 10%. Stefánsson (Stefánsson, V., 1992. Success in geothermal development. Geothermics 21, 823–834) published a statistical study of the drilling results in 31 high-temperature fields in the world. Using these results, it is possible to estimate the expectation value and its limits of error for the subsurface investment in an arbtitrary geothermal field. The results obtained for the range 20–60 MW are summarized as follows:

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	Expectation value USD/kW	Range within one standard deviation USD/kW
Surface cost only	977	762–1192
Total cost in a known field	1267	1062–1692
Total cost in an unknown field	1440	1122–1992

Keywords: Investment cost; Geothermal power plants; Expectation value; Economy of size

1. Introduction

Analyses of the investment costs for geothermal developments are not often found in the literature. It is frequently assumed that development costs are difficult to predict because of the uncertainty involved in geothermal drilling. Another common misconception is that the cost of geothermal drilling is the main obstacle to geothermal development.

Given the fact that the drilling cost of a low-temperature geothermal development (for direct use) is typically some 10–20% of the total development cost, and that the drilling cost for a typical geothermal power plant in a high-temperature field is usually in the range 20–50% of the total cost of such a plant, it is quite obvious that geothermal drilling cannot be blamed exclusively for the uncertainty in geothermal development.

The present paper describes an analysis of the investment costs of geothermal power plants and estimates the expected investment cost level in unknown geothermal fields. Experience and data from Iceland are used in the paper, but similar conditions are expected to apply elsewhere in the world. Figures for cost are based on actual cases in Iceland. Price levels in Iceland are, in general, similar to those in Western Europe and the USA. The investment costs valid for geothermal power plants in Iceland can therefore be considered as representative for some other parts of the world.

2. Development strategy

In the past, geothermal power plants have frequently been built "as large as possible", meaning that an immense effort has been made to determine the generating capacity of the geothermal field prior to development, and the size of the power plant has been selected close to this estimated level. There are several drawbacks to this development strategy and we will give four unfavorable conditions:

a. It is of economic importance to reduce the time lapse between the investment in drilling and the moment when the investment can begin generating income (start of production). Drilling costs are typically in the range 20–50% of the total investment cost of a geothermal power plant. The feasibility of the power plant may therefore critically depend on the production wells being drilled a short time before the start of production. These circumstances can create conflicting goals for the development. Many wells should be drilled and tested at an early stage of the development in order to minimize the risk in the estimate of the generating capacity of the geothermal field, whereas most wells should be drilled as late as possible in order to minimize the investment cost.

b. A reliable knowledge of the generating capacity and other production characteristics of a given geothermal reservoir can only be obtained by observing, for some years, the response of the reservoir to a given production. If it is decided that the power plant is to be developed in one step, the reservoir will have to be tested by means of test-production for some years before the size of the power plant can be determined. This will result in a relatively high cost of investigation to be paid long before generation can start. If a stepwise development is adopted, on the other hand, production from the first unit can be used to monitor the reservoir response and to estimate the generating capacity of the geothermal system.
c. Historically, there is a limited number of geothermal fields where the capacity of the installed surface equipment has been larger than the generating capacity of the field. Such a situation can be avoided by applying a stepwise development of the field.
d. It is frequently observed that the enthalpy of the geothermal fluid changes with time during exploitation. This can easily result in a mismatch between the turbines and the geothermal fluid available in the field. A stepwise development of the field will be of help in maintaining a suitable match between the turbine design and the production characteristics of the geothermal fluid.

The above points indicate that a stepwise development of a geothermal field offers a number of benefits. A major issue here is that the production characteristics of a geothermal reservoir cannot be determined without a proper investigation of the production from the same reservoir. By selecting a relatively small power plant as the first step in the development of the field, the actual production can be used to monitor the response of the reservoir and to estimate the production characteristics of the field. This knowledge will allow us to determine when the next step in field development can be taken and how large this step should be. With this development strategy, the final generating capacity of the field will not be known in detail until the field has been fully developed.

When stepwise development strategy was first adopted in Iceland, it was assumed that 20 MW was a suitable step for developing a high-temperature geothermal field for power generation. This size was selected because this was the largest skid mounted equipment available at that time (1990) and it was considered an advantage that the equipment could be moved to another location if the field under development turned out to be unsuitable for power production. Newer designs of turbines with overlying steam outlet are easier to install than the older types, so larger step units (30 MW) are frequently used today as step units in geothermal development.

This new strategy, to develop all geothermal fields in 20–30 MW units, can make it necessary to have more than one field under development simultaneously. A typical time schedule for developing each step would be 6 years, with the following components:

Reconnaissance	1 year
Surface exploration	1 year
Exploration drilling	1 year
Production drilling and power plant	3 years
Total time	6 years

Decisions with regard to the power plant should be taken on the basis of the results of drilling two exploration wells in the third year of the investigation for the first step. Production drilling is carried out simultaneously with the construction of the power plant.

When electricity generation starts, six years after beginning of investigation, monitoring of the reservoir also starts, and after some three years of reservoir analysis it should be possible to decide whether the next step (20–30 MW) is advisable or not. Allowing three years for this phase, the next unit should be ready six years after the start of the first unit, and so on.

Financial analysis of the stepwise strategy shows that the long-term investment costs for the development of a geothermal field are considerably lower than developing the field in one step. There is a much shorter time lapse before some revenue accrues from the investment, and the production cost of the electricity becomes lower. The geothermal industry in Iceland has adopted a stepwise development of its geothermal fields.

3. Capacity factor

Geothermal power plants are independent of climate and seasons. Climate conditions can influence the cooling capacity of some plants, but the general picture is that geothermal power plants can operate at constant load day-out and day-in all year round. Therefore, it is convenient to operate the geothermal power plants as base load when they are connected to a grid, together with other types of power plants. In Iceland, the average operational time of geothermal plants is about 8000 h per year. In this case, the production units serving the grid are hydro and geothermal plants only (with some oil-fired reserve units), so it is natural that the geothermal plants are used as base load and hydro takes up the variable load. With a different combination of production units serving the grid, a different operational strategy for the geothermal plants might be more suitable. In general, however, the capacity factor of geothermal plants is high, resulting in a favorable production price for each kWh generated.

4. Cost parameters

The investment costs of geothermal plants can ideally be split into two categories: surface equipment (the plant itself and the steam-gathering system) and subsurface investments (drilling the wells). Surface exploration costs are a very small fraction of the total investment cost of geothermal power plants larger than 5–10 MW, but this cost can be classified as surface activity in the cost break-down applied here. One of the benefits of this cost break-down is that the limits of error in the cost estimate for the surface equipment are the same as for other construction work on the surface (buildings, roads, bridges), whereas higher limits of relative error might be expected because of the difficulties in predicting drilling results, and thus the number of steam wells required for the plant. Fig. 1 shows how the total investment cost of a 20 MW power plant in Namafjall, Iceland, depends on the total number of wells required for this power plant. Fig. 1 is based on a detailed project planning report carried out in 1994 (Orkustofnun and VGK, 1994).

Drilling experience in the Námafjall field had indicated that the expected yield of future wells would be on average 4 MW per well. Some 5–6 production wells were therefore required for this 20 MW power plant. Assuming that an additional two wells would be needed for reinjection, the total number of wells required was estimated at 8. From Fig. 1, it can be seen that the total investment cost for this power plant was about 35 million USD, or 1750 USD per installed kW.

It should be noted that the subsurface costs for the 20 MW power plant in Namafjall are estimated at 13 million USD, out of a total cost of 35 million USD, i.e. 37%. The limits of relative error for the subsurface part of the cost estimate are higher than for the cost of the surface equipment. Assuming that the relative error

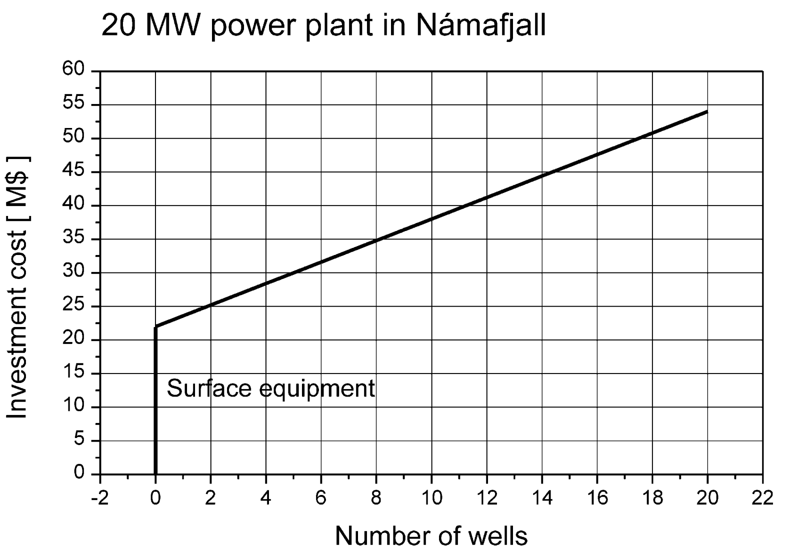

Fig. 1. Investment costs of a 20 MW power plant in Namafjall.

for the surface part is 15% and that for the subsurface part it is 40%, we see that the relative error for the estimate of the total investment is 24%.

Fig. 1 shows that if there was an economy of size present for geothermal power plants, this effect would show up in the surface part of the investment cost. In a given geothermal field, there is a direct proportionality between the size of the power plant and the number of wells required to provide enough steam for the power plant. Recent cost figures for the cost of surface equipment are available in Iceland. The cases discussed here are given in Table 1.

The new power plants at Svartsengi and Nesjavellir are co-generation plants producing both heat and electricity, whereas the plants at Bjarnarflag and Krafla are designed only for electricity generation. In all cases, the turbines considered are typical single-flash units frequently used for electricity generation in high-temperature geothermal fields. The data on surface costs in Bjarnarflag and Krafla are extracted from the detailed project planning reports for the plants at these locations.

Fig. 2 shows the relation between surface costs and the size of the power plants listed in Table 1. The data points define a linear relationship and the best linear fit to the data-points is:

$$\text{Surface cost (million USD)} = (-0.9 \pm 4.6) + (1.0 \pm 0.1) \times \text{MW} \tag{1}$$

and the correlation coefficient is $R^2 = 0.97$. This equation is valid in the range 20–60 MW.

The data presented in Fig. 2 clearly indicate that there is no economy of size for geothermal power plants in the range 20–60 MW. In fact, an attempt to fit a second-order function to the data in Fig. 2 results in a small second-order term for a concave function, meaning that the investment cost is increasing faster than linearly with size.

Table 1
Cost in 2001 USD of surface equipment for various geothermal power plants in Iceland

Location	Size of power plant (MW)	Cost of surface equipment (million USD)	Type of cost estimate	Year
Svartsengi[1]	30	26.16	Actual cost	1999
Nesjavellir[2]	60	62.38	Actual cost	1998
Bjarnarflag[3]	20	23.00	Project planning	1994
Bjarnarflag[3]	40	38.80	Project planning	1994
Krafla[4]	40	41.89	Project planning	1999

[1] Hitaveita Sudumesja (2000).
[2] Morgunbladid 8.4. (1998).
[3] Orkustofnun and VGK (1994).
[4] VGK, Rafteikening and Orkustofnun (2000).

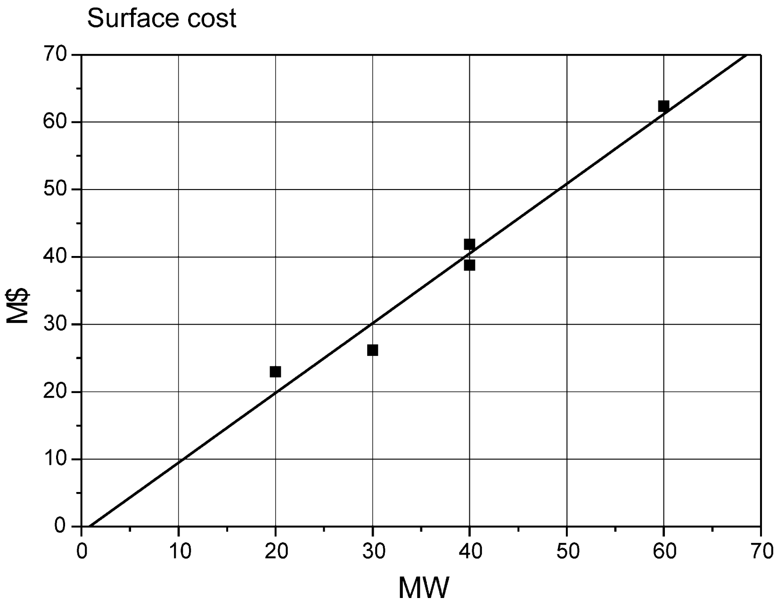

Fig. 2. Relation between surface costs and the size of a power plant.

5. Subsurface costs

Eq. (1) could be adopted as an average cost estimate for the surface cost of typical single-flash geothermal power plants in the range 20–60 MW. For the subsurface part of the cost estimate we use the results of Stefánsson (1992). In that paper, Stefánsson analyzed the result of drilling in 31 high-temperature geothermal fields in the world. He showed that the average yield of wells in any particular geothermal field is fairly constant after passing through a certain "learning period" and gaining sufficient knowledge of the reservoir to site the wells so as to achieve the maximum yield possible.

Fig. 3 shows examples of the results presented by Stefánsson (1992). The average output per drilled km in four geothermal fields is shown as a function of well number in each field. For these fields, in the Philippines and New Zealand, the average yield is about 4–5 MW for each drilled km. The figure also shows that, although the asymptotic yield of all four fields is similar, a different number of wells was required to reach the level of maximum yield of wells in the field.

Table 2 shows the average values for the 31 geothermal fields studied by Stefánsson (1992). Fig. 4 shows the histogram of the yield per drilled km for these 31 fields Stefánsson (1992). If a similar analysis is carried out for the yield of geothermal wells in Iceland alone, a somewhat higher yield is obtained than for the 31 fields reported by (Stefánsson, 1992). The world average is, however, used in this paper in order to underline the worldwide applicability of the method presented in this paper.

The figures presented by Stefánsson (1992) can be used to estimate the average subsurface cost for geothermal power plants. We assume that the average depth of the wells is 1500 m, and that the average cost of such wells is 1.5 million USD

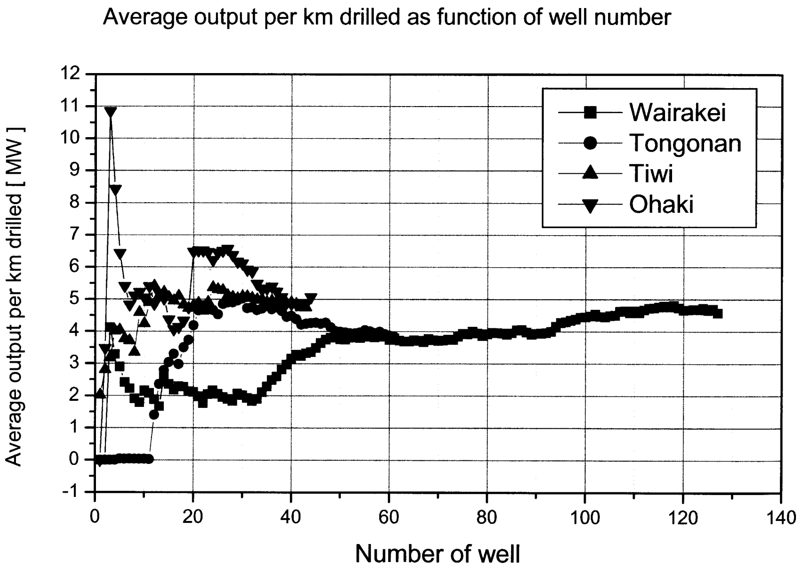

Fig. 3. Average output per drilled km as function of well number in four high-temperature geothermal fields.

Table 2
Average values for 31 geothermal fields (Stefánsson, 1992)

Average MW_e per well	4.2 ± 2.2
Average MW_e per drilled km	3.4 ± 1.4
Average number of wells before max. yield achieved	9.3 ± 6.1

(drilling cost in Iceland as reported by Stefánsson, 2000). The average yield of the 1500 m wells is $1.5 \times (3.4 \pm 1.4) = (5.1 \pm 2.1)$ MW, and the cost per MW is $1.5/(5.1 \pm 2.1) = 0.29$ $(+0.21/-0.09)$ million USD. The cost range is thus from 0.2 to 0.5 million USD per MW, with the most likely value being 0.29 million USD per MW. It should be pointed out that this cost per MW is relatively insensitive to the drilling depth (and drilling cost) because the yield of the wells is referred to each km drilled.

Combining this result with Eq. (1), the expected investment cost in a known geothermal field (second or later steps in the field development) can be estimated as:

$$\text{Cost (million USD)} = (-0.9 \pm 4.6) + (1.29 \; +0.31/-0.19) \times \text{MW} \quad (2)$$

This means that the most likely investment cost for a 40 MW power plant in a known geothermal field is 50.7 million USD and, with one standard deviation limit, the upper and lower levels are 67.7 and 42.5 million USD respectively. This gives the range 1062–1692 USD per installed kW, with the most likely figure being 1267 USD/kW.

For the first step of field development, the "learning cost" has to be added to the cost estimate. This cost is associated with drilling a sufficient number of wells in

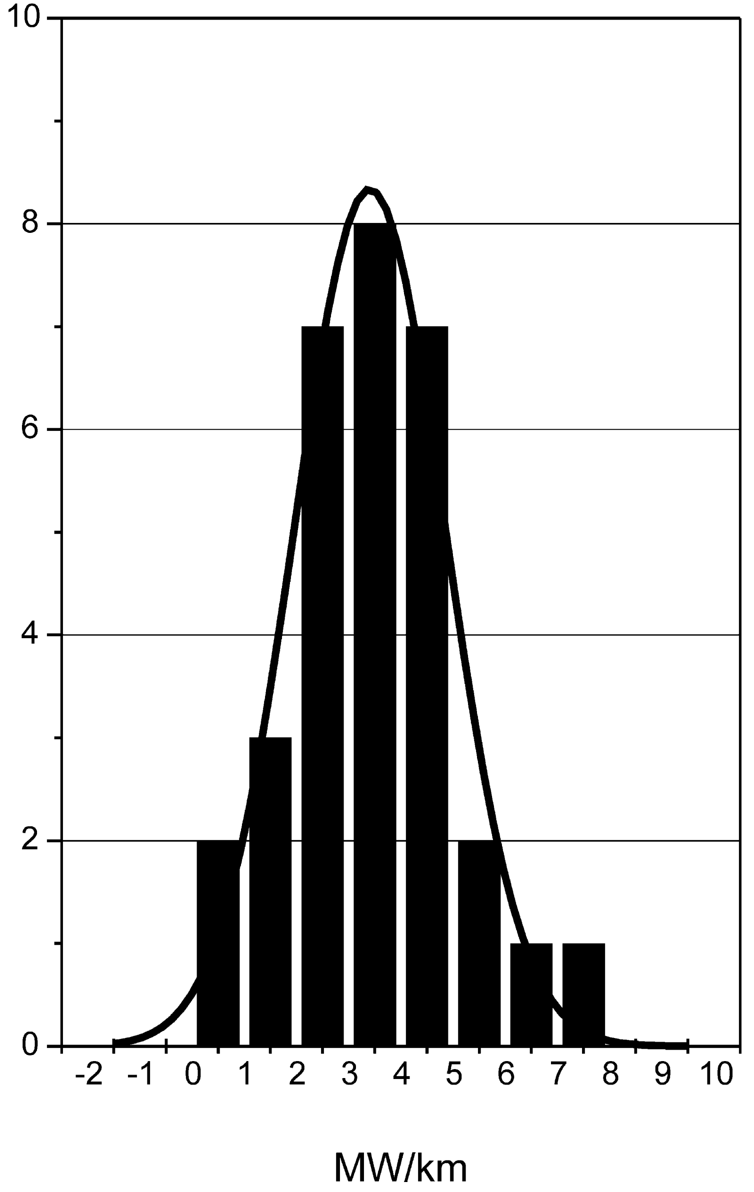

Fig. 4. Histogram for the parameter MW/km from 31 high-temperature fields.

order to know where to site the wells for a maximum yield of drilling. The average number of wells required for this is 9.3 ± 6.1 wells. Assuming that the average yield in the "learning period" is 50% of the yield obtained as the asymptotic value of the field, these circumstances are equivalent to adding the cost of drilling a further

Table 3
Investment costs of geothermal power plants in the range 20–60 MW

	Expectation value (USD/kW)	Range within one standard deviation (USD/kW)
Surface cost only	977	762–1192
Total cost in a known field	1267	1062–1692
Total cost in an unknown field	1440	1122–1992

4.6 ± 3.0 wells to the first development step. Assuming that the cost of each well is 1.5 million USD, the additional cost is 6.9 ± 4.5 million USD.

For the first development step in developing a geothermal field (unknown field), the expected investment cost can be estimated as:

$$\text{Investment cost (million USD)} = (6.0 \pm 9.1) + (1.29 + 0.31/-0.19) \times \text{MW} \quad (3)$$

The most likely investment cost for a 40 MW unit in this case is 57.6 million USD, with the upper and lower limits at 79.1 and 44.9 million USD, respectively. This gives a cost range of 1122–1992 USD/kW with the most likely value being 1440 USD/kW.

6. Conclusions

Statistical methods have been used to estimate the investment costs of geothermal power plants, where a stepwise development strategy is applied. The cost figures obtained are summarized in Table 3.

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