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GEOTHERMAL TRAINING PROGRAMME



LaGeo S.A. de C.V.

FEASIBILITY STUDY: COST ESTIMATION FOR GEOTHERMAL DEVELOPMENT

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ABSTRACT

In this paper, capital costs and cost affecting factors of each project stage from exploration, drilling, power plant construction to operation and maintenance are evaluated. Investment costs for typical geothermal development suggest extreme variability in the cost of components when all project costs (exploration and confirmation, drilling an unknown field, power plant and transmission line) are considered. The variability of the specific capital cost is inversely affected by the resource temperature and the mass flow rate. Based on the geothermal resource quality considered for each technology, the estimated cost for single flash ranges from 2,912 to 5,910 USD₂₀₁₀/kW, for double flash from 2,500 to 6,000 USD₂₀₁₀/kW, and for the organic Rankine cycle the cost ranges from 2,302 to 11,469 USD₂₀₁₀/kW. The range of results matches the costs presented in literature where the temperature range is concentrated, for example in the case of the flash systems, when temperature range is reduced to 200-300°C from 160-340°C, and in the binary system when temperature range is reduced to 140-180°C from 100-180°C. Larger size development of geothermal power plants gives more cost effective values than smaller power plant sizes due to economies of scale. The cost of development for small geothermal power projects depends significantly on drilling cost, transmission cost and resource quality. A critical case is small ORC development: the specific capital cost rises quickly, as resource temperature and mass flow rate decrease (as a result of small power output).

1. GEOTHERMAL DEVELOPMENT PROJECT PHASES

The geothermal development processes are fairly similar in geothermal areas around the world with corresponding modifications and innovations (Dolor, 2006). According to Cross and Freeman (2009), the primary stages of a geothermal developmental cycle are exploration, resource confirmation, drilling and reservoir development, plant construction and power production. Based on this approach, this analysis proposes a four stage breakdown as illustrated in Figure 1.

The four phases of the geothermal energy project shown in Figure 1 could be used as a baseline plan for future feasibility models. In this paper, capital costs and cost affecting factors of each project stage from exploration, drilling, power plant construction to operation and maintenance are evaluated.

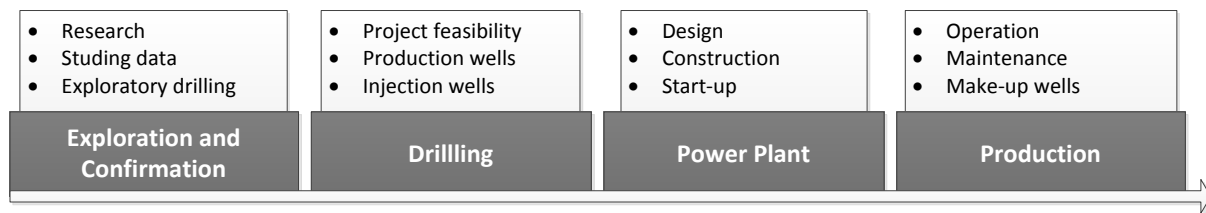


FIGURE 1: Geothermal developmental project phases

2. EXPLORATION AND CONFIRMATION

According to the consulting firm Mannvit (2011), geothermal exploration is *the bridge between early stage ideas for geothermal development and fully committed planning and startup of geothermal production. In the broadest sense, geothermal exploration involves proving the viability of geothermal energy as a practical means of generating power and/or heat in a particular location. The knowledge obtained through exploration is the basis for an assessment of energy producing potential and the subsequent creation of engineering plans and construction cost estimates.*

Resources defined during the exploration phase can be divided into three sub-phases: regional reconnaissance, district exploration, and prospect evaluation. The costs involved in geothermal exploration and development have been widely researched and published. A good deal of this work was summarized by the Geothermal Energy Association on behalf of the US Department of Energy (Hance, 2005). This study points out that the geothermal developers provided exploration cost estimates averaging 173.1 USD/kW. The confirmation phase is defined as drilling additional production wells and testing their flow rates until approximately 25% of the resource capacity needed by the project is achieved. An average cost of 346 USD/kW was suggested when the confirmation phase was considered in tandem with the exploration phase. Using 2010 USD values as an input in the present analysis, the cost in USD/kW was inflated according to the US BLS (2011) inflation calculator.

3. DRILLING

Cost related to drilling is usually the single largest cost and a highly risky component in any geothermal development. Given the circumstances, it is expected that the cost of drilling will be very variable; while this is certainly true to some degree, there are general tendencies. This analysis of drilling costs in Central America is based on the statistical method for estimating drilling investments in unknown geothermal fields presented by Stefansson (2002) who made a statistical study of drilling results in 31 high temperature fields around the world. Using these world average results, and combining them with data from Central America (Bloomfield and Laney, 2005), it is possible to estimate the expected value and its limits of error for drilling investment in this region.

Stefansson (2002) stated 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 possible yield. The average power output (MW) per drilled kilometer in geothermal fields is shown as a function of the number of wells in each field.

TABLE 1: Average values for 31 geothermal fields (Stefansson, 2002)

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

For this estimation, it is assumed that the average depth of the wells is 1,890 m, and that the average cost of such wells is 3.24 million USD as presented in Table 2 (drilling costs in Central America as reported by Bloomfield and Laney, 2005).

TABLE 2: Drilling costs from 1997 to 2000 for Central America and the Azores in 2010 USD (Bloomfield and Laney, 2005)

Depth interval (km)	Number of wells	Total cost (MUSD)	Average depth (km)	Average cost/well (MUSD)
0.00-0.38	1	0.33	0.21	0.33
0.38-0.76	8	12.34	0.60	1.54
0.76-1.14	0	0.00	0.00	0.00
1.14-1.52	5	12.87	1.31	2.57
1.52-2.28	24	77.13	1.77	3.21
2.28-3.04	20	81.57	2.55	4.08
3.04-3.81	3	13.62	3.35	4.54
Total			1.89	3.24

The average yield of the 1,890 m wells is $3.24 \times (3.4 \pm 1.4) = (6.43 \pm 2.6)$ MW, and the cost per MW is $3.24 / (6.43 \pm 2.6) = 0.5 (+0.46/-0.21)$ MUSD/MW.

According to Stefansson (2002), this cost per MW is relatively insensitive to the drilling depth (and drilling cost) because the yield of the wells refers to each km drilled; 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 order to know where to site the wells for a maximum yield from drilling. As shown in Table 1, 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%, 4.6 ± 3.0 wells are adding to the first development step. Incorporating the average cost per well, shown in Table 2, the additional cost is 15.07 ± 9.7 million USD. The estimation for expected drilling investment cost is calculated as follows:

$$\text{Drilling cost million USD} = (15.07 \pm 9.7) + [(0.5 + 0.46/-0.21) * MW] \quad (1)$$

Using 2010 USD values, the cost of wells has been inflated according to the US BLS (2011) inflation calculator.

4. POWER PLANT

Equipment purchase cost estimation is the key driver of the capital cost estimation for a given power plant project. There are three main sources of equipment estimation data: vendor contacts, open literature, and computerized estimating systems (Westney, 1997). In this section, the prices of the main geothermal power plant equipment are collected in the form of correlating equations found in the literature (heat exchangers, compressor, pumps, etc.), communication with developers (turbines and separators) and vendor quotes (cooling tower). The prices are given in terms of appropriate key characteristics of the equipment, such as area (m²), pressure (kPa), and power (kW). Factors for construction materials and performance characteristics other than the basic ones are also included.

4.1 Heat exchangers

The three geothermal systems (SF, DF and ORC) analyzed require a variety of heat transfer steps to produce a suitable prime mover fluid. In order to evaluate the cost of these components, and before

selecting the estimation method, it is necessary to define the size and design of the component. This requires the appropriate duty factor, temperature and pressure differences.

Equipment sizing

In this analysis, the Log Mean Temperature Difference (LMTD) method is applied to calculate the heat transfer area A (Equation 2). Heat transfer in a heat exchanger usually involves convection in each fluid and conduction through the wall separating two fluids. In the analysis, it is convenient to work with an overall heat transfer coefficient U that accounts for the contribution of all these effects on heat transfer. The rate of heat transfer \dot{Q} between the two locations in the heat exchanger varies along the heat exchanger. It is necessary to work with the Logarithmic Mean Temperature Difference ΔT_{lm} (Equation 3), which is an equivalent mean temperature difference between two fluids for an entire heat exchanger (Cengel and Turner, 2005).

The overall heat exchange surface expressed as a function of \dot{Q} , U and ΔT_{lm} can be written as:

$$A = \frac{\dot{Q}}{U \Delta T_{lm}} \quad (2)$$

where

$$\Delta T_{lm} = \frac{\Delta T_1 - \Delta T_2}{\ln\left(\frac{\Delta T_1}{\Delta T_2}\right)} \quad (3)$$

In Equation 3, ΔT_1 and ΔT_2 represent the temperature differences between the two fluids at the inlet and outlet. Table 3 shows the overall heat transfer coefficients used in the analysis of a heat exchanger.

TABLE 3: Overall heat transfer coefficients (Valdimarsson, 2011)

Fluids	U (W/m ² K)
Water – Water	2000
Steam – Water	2000
Water – Isopentane	1200
Isopentane – Isopentane	1200

Estimated equipment cost

Numerous methods in relation to the cost of heat exchangers can be found in the literature. Most of them are presented in the form of graphs and equations for FOB purchase cost as a function of one or more equipment size factors. The equipment cost equation presented by Seider et al. (2003) is incorporated into the calculations here. The equations are based on common construction materials, and for other materials a correction factor is applied. The input parameters are: heat exchanger surface area A_f in ft, design pressure P_d in psig, heat exchanger type and material of construction.

The base cost (C_B) can be calculated as follows:

$$C_B = \exp\{11.0545 - 0.9228[\ln(A_f)] + 0.09861[\ln(A_f)]^2\} \text{ for fixed head} \quad (4)$$

$$C_B = \exp\{11.967 - 0.8197[\ln(A_f)] + 0.09005[\ln(A_f)]^2\} \text{ for kettle reboiler} \quad (5)$$

This base cost calculation counts for certain base case configurations including a carbon steel heat exchanger with 100 psig (690 kPa) pressure with a heat exchanger surface between 150 ft² (13.9 m²) and 12,000 ft² (1,114.8 m²). Correction factors for a different specific heat exchanger are introduced, and the FOB purchase cost for this type of heat exchanger is given by

$$C_P = C_B F_P F_L F_M \quad (6)$$

For different materials the factor F_M is introduced:

$$F_M = a + \left(\frac{D}{100}\right)^b \quad (7)$$

For different operating pressure the factor F_P is introduced:

$$F_P = 0.9803 + 0.018 \left(\frac{P_d}{100}\right) + 0.0017 \left(\frac{P_d}{100}\right)^2 \quad (8)$$

The base heat exchanger purchase cost equation is based on the CE index cost in mid year 2000 (CE=394).

Correcting equipment cost for inflation

Because the cost literature reflects equipment from some time in the past, it is necessary to correct for the cost of inflation. There are several inflation or cost indices in use; here the Chemical Engineering Plant Cost Index (CE index) is used in this analysis. The Chemical Engineering magazine (CHE) publishes the CE index regularly for correcting equipment costs for inflation; the CE indices for December 2010 are used in this analysis (CHE, 2011).

In order to obtain the current cost value of equipment C_2 we use an inflation index I_2 as given by Equation 9.

$$C_2 = C_1 \frac{I_2}{I_1} \quad (9)$$

4.2 Turbine – Generator

If a new piece of equipment is similar to one of another capacity for which cost data is available, then it follows that the estimated cost for turbines can be obtained from a scaling factor by using the logarithmic relationship known as the six tenths factor rule. According to Peters et al. (2003) if the cost of a given unit at one capacity is known, then the cost of a similar unit with X times the capacity of the first is approximately $(X)^N$ times the cost of the initial unit. The value of the cost exponent N varies depending upon the class of equipment being represented; the value of n for different equipment is often around 0.6. The typical value of cost exponent N for the steam turbine included in this analysis is 0.6.

Input parameters: cost and power of known turbine, capacity of estimated turbine.

$$\frac{\text{Cost of equipment}_2}{\text{Cost of equipment}_1} = \left(\frac{\text{Capacity equipment}_2}{\text{Capacity equipment}_1}\right)^N \quad (10)$$

This method is used in combination with the cost indices. Personal conversations with geothermal developers indicate that recent references (2010) used in the estimated purchasing cost for a turbine generator in a single flash process is around 13 million USD for 30 MW, and for double flash an additional 15% of the SF cost is considered. In a recent ORC development in Costa Rica, Marcos (2007) quoted a turbine cost of around 4 million USD for 7.5 MW.

4.3 Compressor

The FOB purchase cost for a typical centrifugal compressor is based on an equation from Seider (2003) where the base cost is given as a function of consumed power. The input parameters are: consumed power P_c in HP and material of construction.

The base cost (C_B) is calculated as:

$$C_B = \exp\{7.2223 + 0.80[\ln(P_c)]\} \quad \text{for centrifugal compressor} \quad (11)$$

This base cost calculation counts for certain base case configurations including an electrical motor drive and carbon steel construction. For other materials, a correction factor F_M is included. For geothermal purposes, stainless steel is used ($F_M = 2.5$).

$$C_P = C_B F_M \quad (12)$$

The base purchase cost equation for the compressor has a CE index of 394. To correct the equipment cost for inflation, compressor CE indices (CE=903) for December 2010 are included (CHE, 2011).

4.4 Pumps

The technical literature for the cost of equipment offers several equations for calculating the approximate cost for centrifugal pumps, but the limitation is the flow range that the cooling water pumps operate in the geothermal power plant. The FOB purchase cost for the centrifugal pump is based on the equation equipment cost presented by Walas (1990). The input parameters are: flow rate Q_{cw} in *gpm* and material of construction.

The base cost for a pump (C_B) is calculated by:

$$C_B = 20 (Q_{cw})^{0.78} \quad \text{for vertical axial flow} \quad (13)$$

Base cost calculations do not include the cost of the motor and are only valid for a flow range between 1,000 *gpm* and 130,000 *gpm*. The material correction factor for stainless steel is ($F_M = 2$). The cost of the motor is calculated by Equation 14. The input parameter is consumed power P_c in HP. The cost of the motor (C_P) is calculated as:

$$C_P = 1.2 \exp[5.318 + 1.084 \ln(P_c) + 0.056 \ln(P_c)^2] \quad (14)$$

These cost calculations are for a motor type which is totally enclosed, fan-cooled and 3,600 rpm.

4.5 Cooling tower

An online vendor quote is easy to get from many companies (e.g. Cooling Tower Systems, Delta Cooling Tower, Cooling Tower Depot). The only requirements are the cooling tower design and operating conditions. In this analysis, the six tenths factor rule is applied, and the cost reference is based

on the cost quoted by Cooling Tower Depot (2011). The typical value of cost exponent N for the cooling tower included in this analysis is 0.9 (Bejan et al., 1996).

4.6 Separation station

A personal conversation with geothermal developers indicated that the cost estimation of a separator can be made based on the mass flow rate capacity of the station. Recent references (2010) gave a cost of 400,000 USD for a mass flow rate capacity of 200 kg/s. Based on this information, in this study the calculation for another separator capacity was obtained using the six tenths factor rule.

4.7 Comparison of PEC between SF, DF and ORC

A comparative study of specific purchased equipment costs (USD/kW) between cycles is presented in Figure 2. The resource temperature ($^{\circ}\text{C}$) and the mass flow rate (kg/s) have a major influence on the plant size (kW) for the SF, DF and ORC power plants. The size determines the cost of various components such as the turbine and heat exchangers which are the major components reflected in the purchasing costs of the main equipment of ORC, SF and DF power plants. An increase in the geothermal resource temperature results in an increase in the efficiency of the power plant and a decrease in the specific cost of equipment.

The temperature of the geothermal resource also affects the selection of the power plant technology. The ORC has the advantage over flash cycles when used for power production from low temperature resources. In the economic evaluation of the purchase costs of main equipment as a function of the resource temperature, it can be seen (Figure 2) that the specific PEC of ORC for temperatures below 180°C is lower than that of SF and DF. However, the specific PEC of ORC rises as temperature drops.

From the same geothermal fluid flow rate, the DF cycle can generate more power than the SF cycle but at an overall increase in cost because of the extra equipment. However, the specific PEC for DF can be lower than for SF for the same fluid rate and higher temperature resources, and for the same temperature resource and higher mass flow rate, which is also associated with power plant size. DF power plants present lower specific PEC than SF for a resource temperature above: 220°C for a mass flow rate of 300 kg/s; 200°C for a mass flow rate of 600 kg/s; 180°C for a mass flow rate of 1000 kg/s.

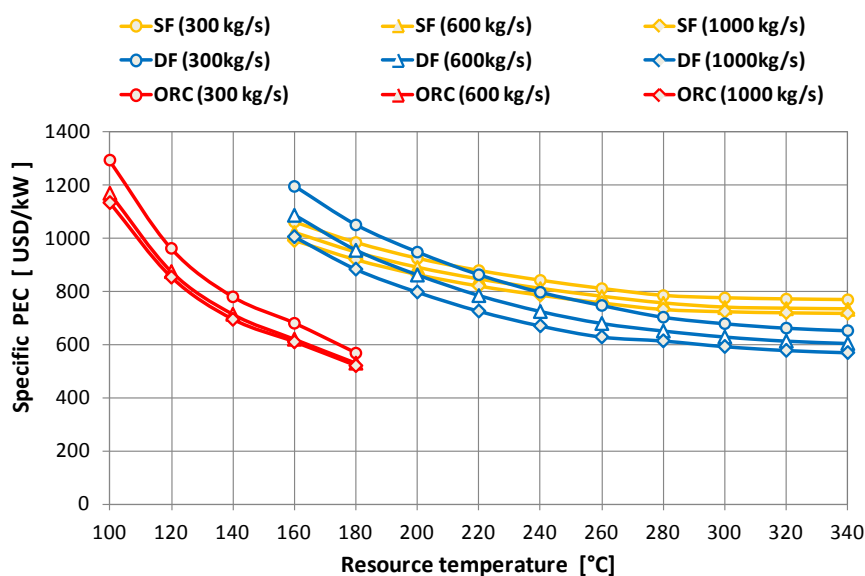


FIGURE 2: Comparison of specific PEC from SF, DF and ORC power plants

4.8 Equipment and construction

The estimation of the total equipment and construction cost is based on the purchase of the main equipment cost which was calculated in the last section. The factor method proposed by Bejan et al. (1996) calculates the cost components of the fixed capital in terms of a percentage of the purchase equipment cost (% of PEC) and direct cost (% of DC). Table 4 shows the calculation of equipment and construction costs.

TABLE 4: Estimation of equipment and construction cost in terms of PEC and DC

Equipment and construction cost estimation	% factor
Purchase equipment cost (PEC)	
Installation of main equipment	33% of PEC
Piping	10% of PEC
Control and instrumentation	12% of PEC
Electrical equipment and materials	13% of PEC
Land	10% of PEC
Engineering and supervisor	25% of PEC
Total direct cost (DC)	
Construction costs	15% of DC
Total	

4.9 Steam gathering

The connection between the wells, the separation station and the power plant network is defined as the steam gathering system or steam field piping. The cost of steam field piping typically depends on the distance from the wells to the power house, the flowing pressure and the chemistry of the fluids. According to Hance (2005), valves, instrumentation, control and data acquisition must be included because they can be significant; the piping and controls can vary from 111 to 279 USD/kW. Using 2010 USD, the estimated cost USD/kW has been inflated according to the US BLS (2011) inflation calculator.

4.10 Power transmission lines

Power transmission lines are expensive; therefore, geothermal power plants need to construct them near the resources. Distance, accessibility and capacity of transmission play key roles in the cost of constructing transmission line. The unit cost per kilometer based on flat land/rural setting, engineering and construction costs, for 69 and 115 kV double circuits, the cost is between 0.66 and 0.92 MUSD/km; for a 230 kV double circuit, the cost is between 0.79 and 0.91 MUSD/km (Ng, 2009). Using 2010 dollar values, the estimated cost USD/km has been inflated according to the US BLS (2011) inflation calculator. Scaling economies are particularly important for transmission costs. Differently sized power plant projects should have similar transmission requirements. Specific transmission costs for larger projects will be 10 times smaller since this cost will be shared out over a much larger power output (Hance, 2005). In this analysis a fixed distance of 10 km is assumed for calculating the power line transmission cost in all scenarios.

5. OPERATION AND MAINTENANCE

Power plant and steam field O&M costs correspond to all expenses needed to keep the power system in good working order. Most articles present O&M cost figures which exclude make up drilling costs.

In this study, however, 2.8 UScents/kWh is used as the total average O&M cost presented by Hance (2005); this O&M cost includes power plant maintenance, steam field maintenance and make up drilling costs. Using 2010 USD values, the O&M estimate cost has been inflated according to the US BLS (2011) inflation calculator.

6. CAPITAL COST OF GEOTHERMAL DEVELOPMENT

Capital cost for geothermal development includes exploration, drilling and power plant. Most of the estimations are based on related literature, which present average cost figures. Geothermal developers can achieve better accuracy if they can acquire updated market information.

Table 5 shows a summary of costs for scenario 1 (SF, 300 kg/s, 240°C) calculated as explained in previous sections. The capital costs estimated according to this methodology for a different geothermal resource (mass flow and temperature) and different power plant technology will be used as input in the financial modeling. Figure 3 illustrates the breakdown of the total capital cost of geothermal development for scenario 1. This includes all the costs associated with total investment where the plant cost is approximately 50%, the drilling cost is 27%, exploration and confirmation costs total 8%, the power line transmission cost is 8% and the steam gathering system cost is 7%.

TABLE 5: Estimated cost of geothermal power plant development for single flash scenario 1 (27.7 MW): 300 kg/s and 240°C

Category	Sub-category	Nominal value	
		Value	Units
Exploration	Exploration	173	USD/kW
	Confirmation	173	USD/kW
	Total exploration	346	USD/kW
Drilling	Known field	504	USD/kW
	Unknown field	1,047	USD/kW
	Total drilling	1,047	USD/kW
Power plant	Steam gathering	279	USD/kW
	Equipment and construction	1,964	USD/kW
	Transmission power line	840,000	USD/km
	Total power plant	2,546	USD/kW
O&M	Total O&M	2.8	USD¢/kWh

6.1 Capital cost of single flash power plant

Figure 4 shows the specific capital cost (SCC) of SF in USD/kW for exploration and confirmation, drilling and power plant as a function of the resource temperature for different mass flows. The SCC decreases as the resource temperature increases from 160 to 340°C. SCC for SF power plants varies from 3,474 to 2,028 USD/kW for 300 kg/s; from 2,928 to 2,002 USD/kW for 600 kg/s; from 2,736 to 2,000 USD/kW for 1,000 kg/s. SCC for SF drilling varies from 2,090 to 721 USD/kW for 300 kg/s; from 1,295 to 610 USD/kW for 600 kg/s; from 977 to 566 USD/kW for 1,000 kg/s.

6.2 Capital cost of double flash power plant

Figure 5 shows the specific capital cost (SCC) of DF in USD/kW for exploration and confirmation, drilling and power plant as a function of the resource temperature for different mass flows. The specific costs decrease as the resource temperature increases from 160 to 340°C. SCC for DF power plants varies from 3,761 to 1,745 USD/kW for 300 kg/s; from 3,070 to 1,616 USD/kW for 600 kg/s; from

2,736 to 1,594 USD/kW for 1,000 kg/s. SCC for DF drilling varies from 1,893 to 701 USD/kW for 600 kg/s; from 1,196 to 600 USD/kW for 600 kg/s; from 1,025 to 560 USD/kW for 1,000 kg/s.

6.3 Capital cost of organic Rankine cycle power plant

Figure 6 shows the specific capital cost (SCC) in USD/kW for exploration and confirmation, drilling and power plant as a function of the resource temperature for different mass flows. The specific costs decrease as the resource temperature increases from 100 to 180°C. SCC for ORC power plants varies from 3,020 to 1,325 USD/kW for 300 kg/s; from 2,729 to 1,223 USD/kW for 600 kg/s; from 2,646 to 1,215 USD/kW for 1,000 kg/s. SCC for ORC drilling varies from 8,103 to 1,305 USD/kW for 300 kg/s; from 4,302 to 902 USD/kW for 600 kg/s; from 2,781 to 741 USD/kW for 1,000 kg/s.

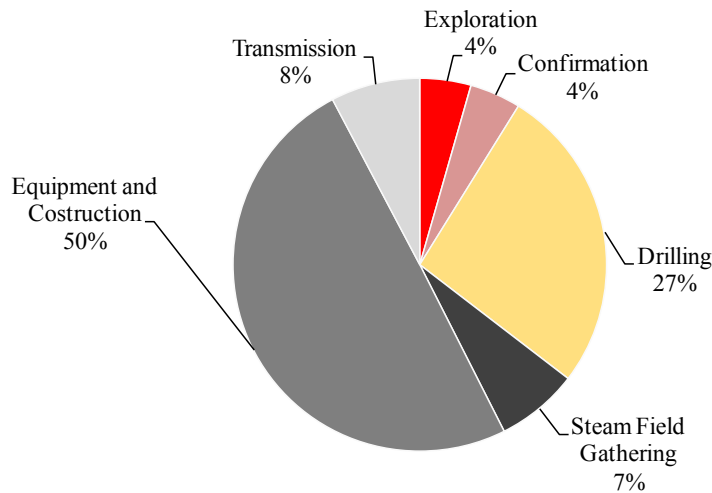


FIGURE 3: Cost breakdown for SF geothermal development in % of total; scenario 1: (27.7 MW): 300 kg/s and 240°C

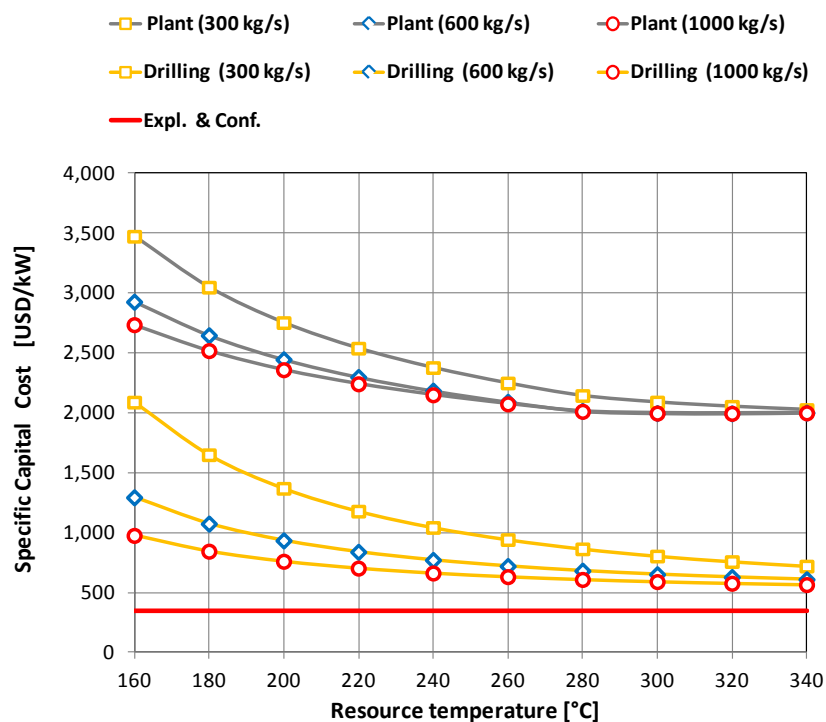


FIGURE 4: Specific capital cost of geothermal development for SF power plant

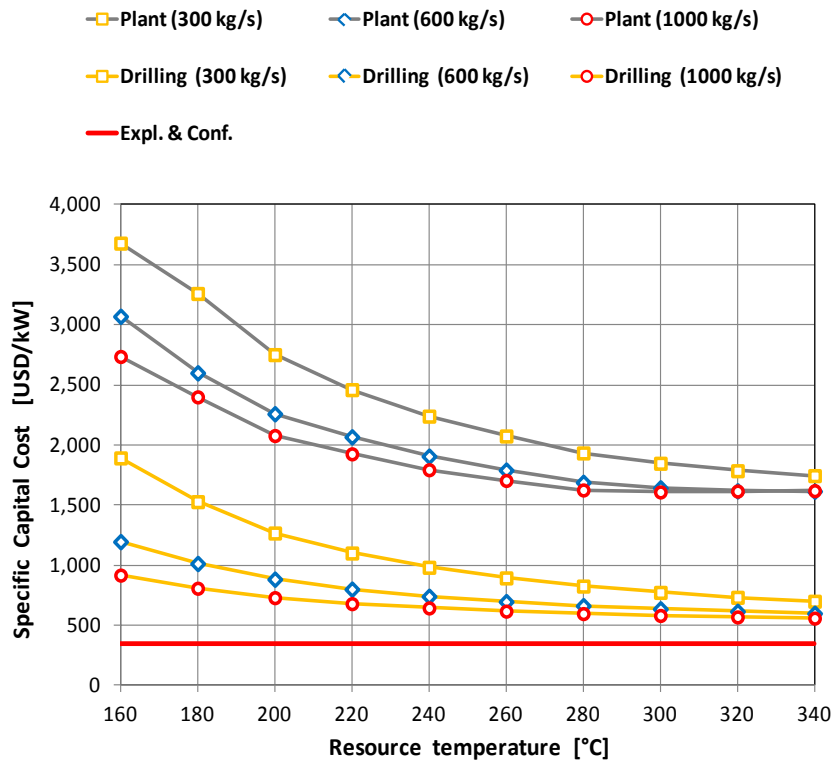


FIGURE 5 Specific capital cost of geothermal development for DF power plant

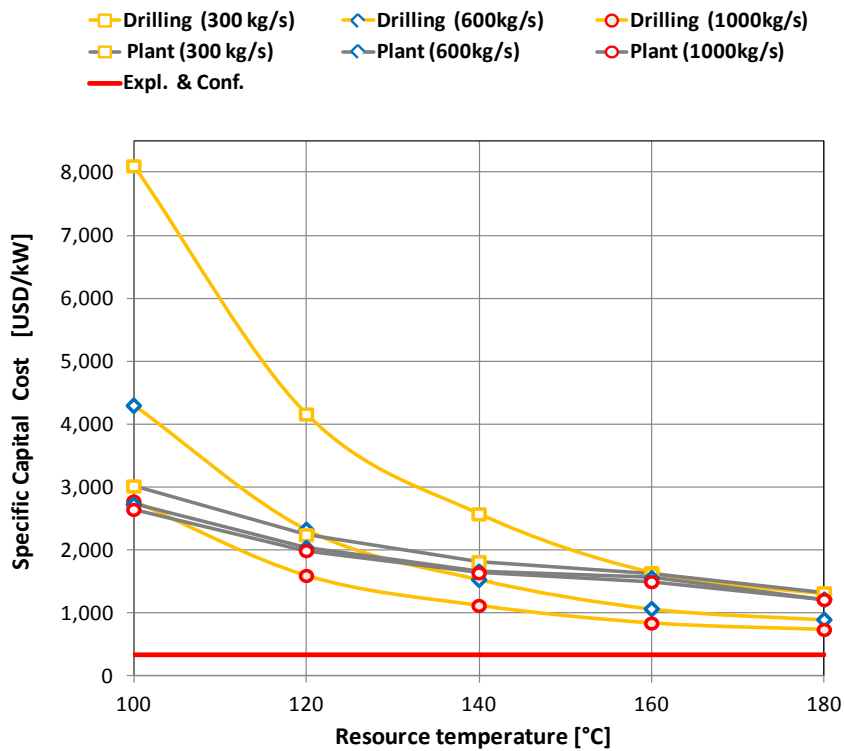


FIGURE 6: Specific capital cost of geothermal development for ORC power plant

6.4 Comparison of capital costs between SF, DF and ORC

Figure 7 compares the specific capital cost as a function of the resource temperature for different mass flow rates and power plant technologies. As shown in the figure, all the technologies in this study anticipate that a larger sized power plant has more cost effective values than smaller sized plants as reflected by scaling economies.

The specific capital cost (SCC) for ORC ranging between 11,400 and 2,300 USD per installed kW, for the resource temperature (100-180°C), and mass flow rate (300 kg-1,000 kg/s) was examined. The SCC of ORC rises quickly, exponentially, as the resource temperature and mass flow rate decrease (as a result of small power output). This occurs because the cost is affected by drilling and transmission line costs. For 300 kg/s at 180°C, the cost of drilling is 35% and transmission lines 13% of the total; at 100°C, drilling costs are 52% and transmission lines 26% of the total.

The SCC for SF, which ranges between 5,910 and 2,940 USD per installed kW, and the SCC for DF, which ranges between 6,000 and 2,500 USD per installed kW at resource temperature (160-340°C) and mass flow rate (300-1,000 kg/s), were examined. The SCC of DF presents lower values than SF for a resource temperature above 200°C at all the mass flow rate scenarios. For resource temperatures between 220 and 180°C, the SCC of SF presents lower values than DF. Finally, for resource temperatures between 180 and 160°C, the SCC of ORC has lower values than either SF or DF.

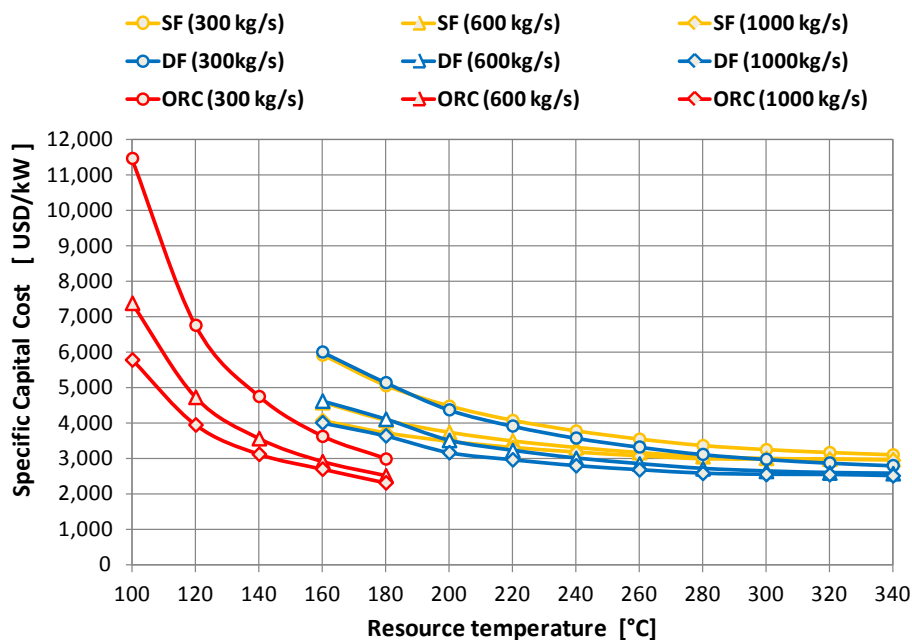


FIGURE 7: Comparison of specific capital costs of geothermal development

6.5 Literature review of capital costs of development

The main limitation for estimating costs is the acquisition of up-to-date data on prices for geothermal power plants, primarily because of the proprietary nature of this information. Source data for Figure 8 are taken from two sources: 1) the “Next Generation Geothermal Power Plants” (EPRI, 1996), where the estimation of cost is for nine geothermal projects in the USA located at different resources with various temperature characteristics; from research by EPRI, Hance (2005) reports that the apparent cost increase of the steam power plant corresponding to the 274°C resource temperature project is explained by other site and resource characteristics; 2) the “Assessment of Current Costs of Geothermal Power Generation in New Zealand (2007 Basis)” (SKM, 2009), a study which developed a band of estimated

specific capital costs for geothermal resources in New Zealand settings from an analysis of 32 assumed scenarios. Using 2010 USD values, the costs have been inflated according to the US BLS (2011) inflation calculator.

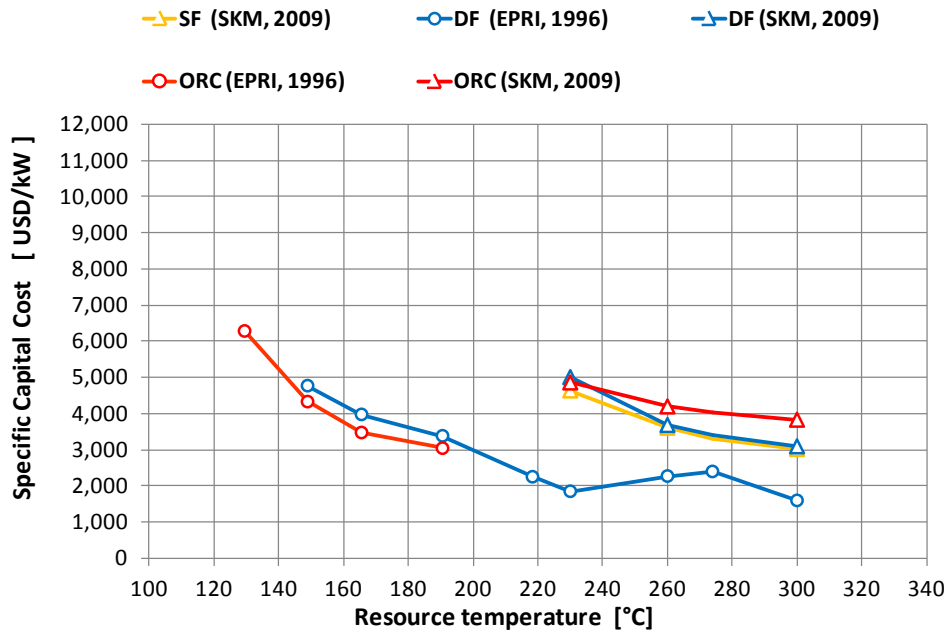


FIGURE 8: Literature review (EPRI, 1996; SKM, 2009): specific capital cost of geothermal developments as function of resource temperature (2010 USD); Note: the specific capital cost from: a) EPRI (1996): 129-300°C resource/50 MW plant size. b) SKM (2009): 230°C resource/20 MW plant size; 260-300°C resource/ 50 MW plant size; values from low enveloped wells; 0.7 as NZD/USD exchange rate (year 2007)

Table 6 illustrates data from a few authors about the specific capital costs of geothermal development for SF, DF and ORC power plants. Hance (2005) has drawn attention to the fact that even though some articles may present average cost figures for geothermal power projects, the cost figures provided frequently hide from view the extreme variability of the cost of components, financing costs and almost none consider the cost of transmission. Research by SKM (2009) observed that further useful discussions on factors affecting the cost of geothermal power development were presented by Sanyal (2005) and Hance (2005), but SKM emphasized that “the details in those papers are specific to the USA and these costs are now significantly out of date, having been largely gathered over the period 2000 to 2003”.

TABLE 6: Literature review: specific capital costs of geothermal development (2010 USD)

Technology	Specific capital cost (USD/kw) (2010 USD)		Author
	Min	Max	
Non specified	1,896	2,962	(Sanyal, 2005)
ORC	3,400	4,240	(World Bank, 2006)
ORC	3,040	6,283	(EPRI, 1996)
ORC	2,481	3,848	(EPRI, 2010)
Flash	2,090	2,600	(World Bnk, 2006)
Flash	3,049	4,065	(Cross and Freeman, 2009)
Flash	1,974	3,038	(EPRI, 2010)
Dual flash	1,595	4,740	(EPRI, 1996)

REFERENCES

- Bejan, A., Tsatsaronis, G., Mora, M., 1996: *Thermal design and optimization*. John Wiley & Sons, Inc, New York, NY, United States, 522 pp.
- Bloomfield, K.K., and Laney, P.T., 2005: *Estimating well costs for enhanced geothermal system applications*. Idaho National Laboratory for the US DOE, Idaho Falls, Idaho, USA, 101 pp. Web: http://geothermal.inel.gov/publications/drillingrptfinal_ext-05-00660_9-1-05.pdf
- BLS, 2011: *CPI inflation calculator*. Website: http://www.bls.gov/data/inflation_calculator.htm
- Cengel, Y.A., and Turner, R.H., 2005: *Fundamentals of thermal-fluid sciences* (2nd edition). McGraw-Hill, New York, NY, United States, 1206 pp.
- CHE, 2011: *Economics indicators, 118-4*, April 2011. Website: <http://www.che.com/>
- Cooling Tower Depot, 2011: *Online tool for design, pricing, selection and optimization of cooling tower*. Website: <http://www.ctdepotinc.com/content/cooling-towers>
- Cross, J., and Freeman, J., 2009: *2008 geothermal technologies market report*. National Renewable Energy Laboratory, report TP-6A2-46022, 46 pp. Web: http://www1.eere.energy.gov/geothermal/pdfs/2008_market_report.pdf
- Dolor, F.M., 2005: Phases of geothermal development in the Philippines. *Papers presented at "Workshop for Decision Makers on Geothermal Projects and Management", organized by UNU-GTP and KengGen, Naivasha, Kenya*, 10 pp. Web: <http://www.os.is/gogn/unu-gtp-sc/UNU-GTP-SC-01-05.pdf>
- EPRI, 1996: *Next generation geothermal power plants*. Prepared for U.S. Department of Energy, Bonneville Power Administration, Southern California Edison Company, and Electric Power Research Institute, report EPRI TR-106223, 184 pp.
- Hance, C.N., 2005: *Factors affecting costs of geothermal power development*. Geothermal Energy Association, Washington DC, United States, 12 pp.
- Mannvit, 2011: *Geothermal exploration*. Website: <http://www.mannvit.com>
- Marcos, A.G., 2007: *Technical-economic feasibility analysis of a geothermal power plant based in Latinoamerica*. Universidad Pontifica Comillas, Spain, BS thesis, 120 pp.
- Ng, P., 2009: Draft unit cost guide for transmission lines. *Presented at Stakeholder Meeting, Folsom, CA, United States*, 7 pp. Website: <http://www.caiso.com/2360/23609c2864470.pdf>
- Peters, M.S., and Timmerhaus, K.D., 2003: *Plant design and economics for chemical engineers* (5th edition). McGraw-Hill Companies, Inc., New York, NY, United States, 1008 pp.
- Sanyal, S., 2005: Cost of geothermal power and factors that affect it. *Proceedings World Geothermal Congress, Antalya, Turkey*, 10 pp. Web: <http://www.geothermal-energy.org/pdf/IGAstandard/WGC/2005/0010.pdf>
- Seider, W.D., Seader, J.D., Lewin, D.R., 2003: *Product and process design principles: Synthesis, analysis, and evaluation* (2nd edition). Wiley, New York, NY, United States, 820 pp.

SKM, 2009: *Assessment of current costs of geothermal power generation in New Zealand (2007 basis)*. Sinclair Knight Merz, Auckland, New Zealand, 82 pp. Web: http://www.geothermal-energy.org/pdf/IGAstandard/AGEC/2009/Quinlivan_2009.pdf

Stefansson, V., 2002: Investment cost for geothermal power plants. *Geothermics*, 31-2, 263-272.

Valdimarsson, P., 2011: Geothermal power plant cycles and main components. *Presented at "Short Course on Geothermal Drilling, Resource Development and Power Plants"*, organized by UNU-GTP and LaGeo, in Santa Tecla, El Salvador, 24 pp. Web: <http://www.os.is/gogn/unu-gtp-sc/UNU-GTP-SC-12-35.pdf>

Walas, S.M., 1990: *Chemical process equipment: Selection and design*. Butterworth-Heinemann Ltd., Boston, MA, United States, 755 pp.

Westney, R., 1997: *The engineer's cost handbook tools for managing project cost*. Marcel Dekker, Inc., New York, NY, United States, 749 pp.