Presented at Short Course on Geothermal Project Management and Development, organized by UNU-GTP, KenGen and MEMD-DGSM, at the Imperial Botanical Beach Hotel, Entebbe, Uganda, November 20-22, 2008.

UNITED NATIONS
UNIVERSITY
GEOTHERMAL TRAINING PROGRAMME

KenGen DGSM

GEOTHERMAL RESOURCE EVALUATION: KEY ELEMENTS

Zosimo F. Sarmiento
Filtech Energy Drilling Corporation (FEDCO)
Tesco Compound, RMT Industrial Complex
Tunasan, Muntinlupa City, 1773
PHILIPPINES
sarmiento@fedcophil.com

ABSTRACT

There has been a significant advancement in geothermal development during the last 15 years with the introduction of new techniques in locating more precisely the sweet spot of a targeted geothermal resource. However, the key elements that constitute a thorough evaluation of a geothermal resource remain the same and these are discussed in this paper. Examples from the Philippines and Iceland using volumetric reserves estimation and numerical modelling reveal that these methods could be both reliably used in sizing up the geothermal resource depending on the amount of data and the stage in which the two techniques are applied. Essential to the technical and commercial viability of the project is the confirmation that the reservoir fluids do not impose constraints on the wellbore casing and surface facilities as a result of scaling and corrosion from the reservoir fluids.

1. INTRODUCTION

Geothermal resource evaluation (*resource assessment*) is a process of evaluating surface discharge and downhole data, and integrating it with other geoscientific information obtained from geological, geophysical and geochemical measurements. The main focus of geothermal resource evaluation or resource assessment is to confirm that there exists a geothermal resource that could be exploited at a certain capacity for a certain period with well defined fluid characteristics and resource management strategies to ensure production sustainability over a long term period. Resource evaluation serves as a mechanism to verify if the project may be carried out from a technical standpoint by 1) defining the technical characteristics, selecting the best conditions after a technical and economical comparison of various development alternatives and 2) in choosing the type of plant and equipment design that would define their functional characteristics, their cost and implementation schedule and 3) assessing costs and benefits, economic and financial comparisons out of various alternatives as part of an overall project technical and financial feasibility studies.

An assessment of geothermal resources can be made during the reconnaissance and exploratory stage prior to well drilling; typically dealing with the extent and characteristics of the thermal surface discharges and manifestations, geophysical boundary anomaly, and the geological setting and subsurface temperatures inferred from geothermometers. The main feature of this evaluation is the presentation of a conceptual or exploration model that pinpoints the possible heat source and host of the geothermal reservoir. The results of this study serve as the basis for drilling shallow and deep exploratory wells to confirm the existence of a resource.

A discovery well drilled during the exploratory stage provides the basis for refining the preliminary conceptual model. By incorporating the results of drilling and well measurements and testing, reserves estimation needed in establishing the size of the reservoir and numerical modelling used in forecasting the future performance of the field can be conducted. Moreover, when planning to expand the capacity of an operating field, a resource assessment will describe the overall production history to show if additional reserves may be available to supply steam to the power plant.

This paper discusses all the possible elements of a geothermal resource assessment typically applied in the Philippines. The choice on the type of plants and equipment to fit into the geothermal resource is discussed further in other papers to be presented at this same conference.

2. THE GEOTHERMAL RESOURCE

2.1 Location

With a portfolio of various geothermal prospects, investors consider the location of a geothermal prospect as a primary factor in their project selection. Projects for exploration and development are ranked by looking first at the various risks associated with the resource characteristics or quality of fluids, size, geological risks or hazards and location with respect to the load centre or market. Given the same resource risks and characteristics, prospects that are close to the load centres and transmission grid are more likely to be chosen by investors for exploration and development. It also favours a project if the government prioritizes the development of infrastructures in the area where the resource is located. Prospects located in national parks and requiring special legislations before permits are issued for development are more likely to be at the end of the wish list of investors.

2.2 Stage 1: Surface exploration program

A geothermal exploration program is usually implemented in three phases starting from (1) a due diligence work which is carried out by thoroughly reviewing available information related to previous investigations of hot springs, fumaroles, silica mounds, solfataras and alteration zones as well as air-photo analyses and remote sensing studies, (2) field reconnaissance surveys including primarily the acquisition of geology and geochemistry data with a glimpse of what is expected on the environmental aspects of the area and 3) detailed exploration surveys consisting of geological mapping, geochemical sampling and geophysical measurements that can be used to delineate a potential geothermal reservoir and assist in the designation of possible exploration drilling targets.

In the Philippines, due diligence work is carried out through the regional identification of a prospect by identifying regional targets based on the association of most high temperature geothermal fields in the Philippines with the Philippine Fault; an active, left-lateral, strike slip fault dotted with Pliocene-Quaternary volcanoes, that forms a discontinuous belt from Northern Luzon to Mindanao. The Philippines has about 71 known surface thermal manifestations associated with decadent volcanism (Alcaraz et al., 1976). These are distributed in 25 volcanic centres as hot spouts, mud pools, clear boiling pools, geysers, and hot or warm altered grounds.

The results of a due diligence study rank the various geothermal prospects that have shown potential for exploration and development by carefully looking into the intensity and significance of the different thermal manifestations observed in the area. Immensely hot and widespread occurrences of thermal manifestations indicate a greater potential for a high temperature and large size reservoir. Acidic fluids are less preferred than the more benign fluids in view of the constraints imposed on handling the corrosion effects on casings and pipelines as well as the associated reservoir management problems during exploitation. The ranking of the field based on such geologic and geochemical parameters are then produced for selection and prioritization in each of the company’s future project portfolios. This technique resulted in achieving a very high success ratio in the Philippines, by being able to discover high temperatures fields with exception of some areas that are lacking in permeability and those that have exhibited acid and magmatic fluids.

The field reconnaissance surveys will confirm what has been reported and seen from the areal photos and satellite images. Geologists and geochemists collect both rock and fluid samples, map out major surface manifestations, and then document all the observations that are significant to all the thermal areas for further investigations. The report should show the probable areal boundaries by which the detailed geological, geochemical and geophysical surveys will be conducted. It is on the basis of the results of the reconnaissance surveys that a budget is prepared to cover the expected cost of the detailed exploration surveys.

Following the identification of a more potentially resourceful area, detailed surface geological mapping, geochemical sampling and geophysical measurements are conducted. The results of the multi-disciplinary works are then integrated to draw out a hydrological model of the system, where the postulated upflow and outflow areas are described.

Previously the Philippines have been very successful in using Schlumberger resistivity measurements in discovering some of the operating geothermal fields in the country today. But it can’t be denied that more exploratory wells had to be drilled subsequently than today before the main sweet spots in those fields were identified. Recent application of Magnetotellurics (MT), which are found to have been able to predict more precisely the more drillable productive sections of the reservoir in many parts of the world, still have to make its mark in the Philippines, given the complex geological setting of the remaining areas that are being offered for concessions. We have yet to discover a new geothermal field using this method.

With the construction of a conceptual or exploration model of the field from the results of the detailed surface exploration techniques, a pre-feasibility report is also prepared which similarly touches on preliminary cost estimation, financial analyses, market studies and environmental impact review.

2.3 Stage 2: Exploration drilling program

In view of the large drilling cost (of 4-5 million dollars per well) and the associated risk in hitting a good production well, it is at this stage when the need for a well-defined financial risk management strategy and instruments becomes extremely important. In the oil and gas industry, farm-in agreements are usually resorted to where additional investors or consortiums partners are invited to share in the cost of drilling. Financial institutions and other companies are willing to advance the cost of drilling in favour of a carbon trade mechanism.

The local geothermal industry has explored to an advanced stage 22 distinct resources in the Philippines. Their development history has a general trend. Upon the integration of the multi-disciplinary exploration data from geology, geochemistry and geophysics for a selected area, a preliminary conceptual model is proposed. Drilling of 2-3 deep exploration wells ensues to validate the hydrological model and to confirm the existence of a geothermal system. Potential targets are identified within the closure of a resistivity or electrical sounding anomaly based on their chances of striking the upflow zones, penetrating permeable structures at depths. The first well is usually targeted towards the main upflow zone, where the chance of drilling a discovery well is high. The other two wells are drilled to probe for the lateral extension of the area; usually to block a well field equivalent to at least 5 km^2, sufficient enough for committing to a 50-100 MW generation potential. Once the existence of a geothermal system is confirmed after preliminary drilling, a resource assessment follows to determine the resource power potential. If the quality of the fluids is such that it could be used for commercial production, a volumetric estimate of the reserves is used for initially committing the size of the power station. The development of Mindanao I typified this approach where the results of the first two exploratory wells were used as a basis for building the 2 x 52 MW power station (Figure 1).

Targeting the first well is the most difficult decision to make in a new project as its results may affect the final outcome of the project, especially if the results are not encouraging. If this happens, the decision to pursue drilling of the second well hinges fully on whether additional targets differed significantly and/or is entirely different on the first target. The third well is usually drilled only after the second well gives promise or provides a new perspective on the understanding of the prospect. Otherwise, it is cancelled.

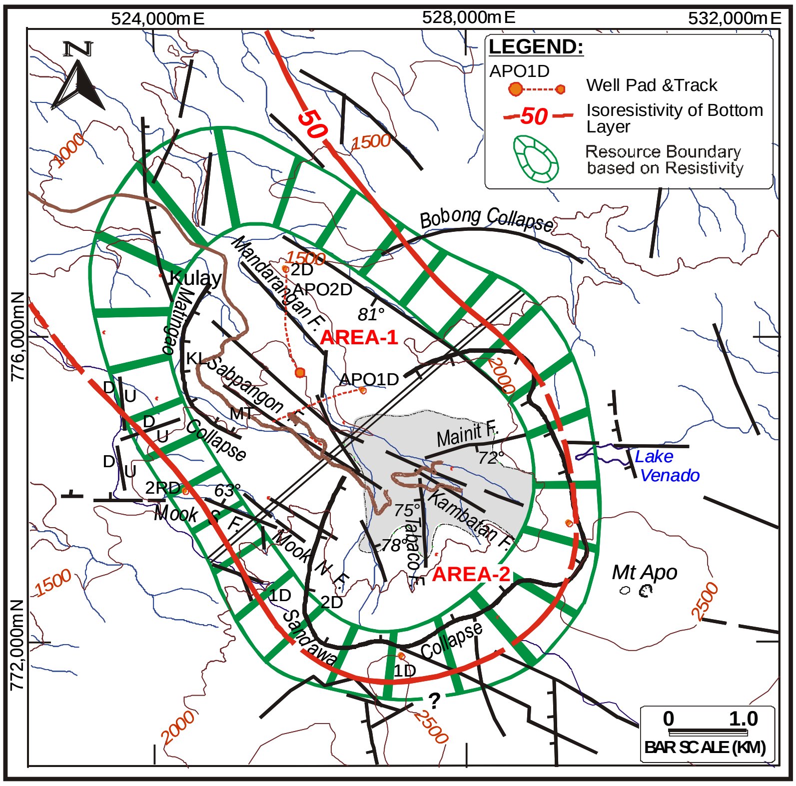

FIGURE 1: Exploratory well location map showing provisional resource boundary for Mindanao geothermal field. (Modified from Delfin et al, 1992)

2.4 Geology of the exploration wells

The subsurface geologic data indicates the equilibrium temperatures of minerals penetrated by the well from the top of the reservoir down to bottom. Obvious from the results are the alteration minerals commonly found in geothermal systems associated with a high temperature resource. Typical of these minerals are the elite, smectite and epidote. When these temperatures are compared with measured downhole temperatures, the relationship of the alteration minerals with respect to the equilibrium state and maturity of the system is established. If the alteration minerals indicate temperatures much higher than measured temperatures, a relict geothermal system or waning geothermal resource exists. Cooling of the fluids might have also taken place. Mineral assemblages like alunite are usually associated with acidic fluids and therefore their detection during drilling gives warning that the zone by which it was detected may have to be isolated. Other clay minerals are used during drilling to predict temperatures at depth like those of kaolinite, smectite and illite to be in the range of temperatures < 230°C; smectite, illite and quartz with fewer amounts of calcite and chlorite to be in the range of temperature >230°C; epidote, albite, calcite and anhydrite to indicate moderate temperatures of 200-300°C and potassic minerals near hot fluids to be indicative of >300°C of magmatic and high salinity fluids.

Based on the circulation losses encountered during drilling, intersection of faults postulated from the surface are confirmed which would then serve as the basis for future targeting in other wells. Therefore, with temperatures and permeability structures confirmed to be present in the reservoir, exploration risks are greatly reduced.

2.5 Well measurements

Stable well temperatures and pressures are established by conducting regular well measurements after drilling completion, usually from the start of well recovery until the wells are flowed for testing. Stable temperatures are determined and used for contouring the temperature distribution and delineating the hottest (upwelling) and outflow regions of the reservoir. The stable pressures are also plotted from the main pivot points or control points in each of the wells that approximate the pressure of the reservoir.

Immediately after drilling, injection tests are conducted by pumping water at various flow rates to be used in establishing the permeable zones and injectivity index of the well. Transient pressure tests are also conducted where pressures are monitored at given depths after pump shut off to determine well permeability (kh) and skin factor. The data are then used to establish if the well was damaged during drilling and to determine whether chemical treatment has to be done to restore its permeability. Figure 2 Shows the injectivity data from the well, as well as the damage represented by the skin pressure incurred during drilling.

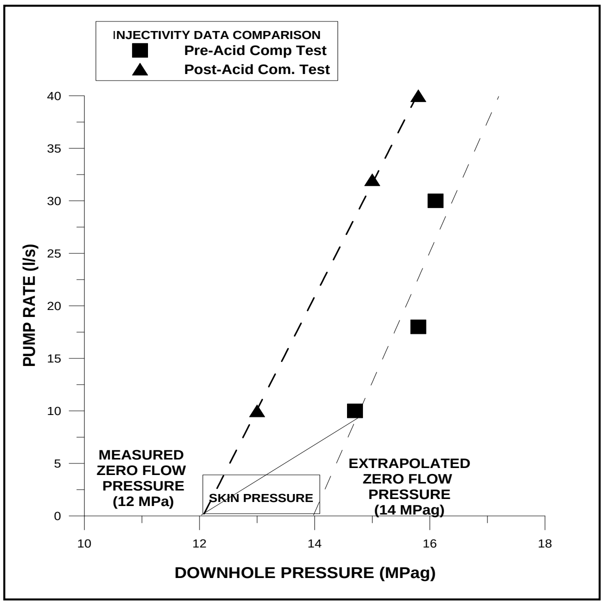

FIGURE 2: Downhole pressure measured during an injectivity test before and after acidizing.

2.6 Well testing results

As soon as the wells attained sufficient temperatures and pressures to be able to flow by itself or sustain flow after well stimulation, discharge testing is pursued to establish the commercial characteristics and the quality of the brine and steam from the wells. Flowing wellhead pressures are determined by subjecting the well to various choked conditions using back-pressure plates or orifices until a maximum discharge pressure is reached. From the data, the output at various wellhead pressures are calculated and used in optimizing the most likely turbine inlet pressure.

Wells are also classified based on the pattern of flows at different WHPs. Wells that do not change in flow with increasing WHPs are formation controlled; while wells with decreasing output with increasing WHP's are wellbore controlled. The first type of wells indicate that well output is limited by the formation while the second type of well means that sufficient permeability has been encountered in the formation and, therefore, output is restricted only by the size of the casing installed. If patterns are established during the early development stage, big holes are designed for production and injection wells to reduce the total number of wells to be drilled. Figure 3 demonstrates a typical output curves of wells that are wellbore controlled.

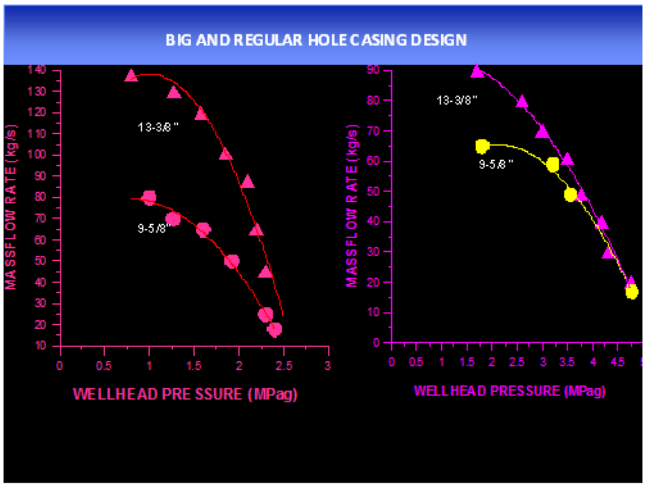

FIGURE 3: Plots of well output (massflow) against flowing wellhead pressure (WHP) showing the large increase in mass flow on wells that are wellbore controlled.

2.7 Well geochemistry

Water and gas samples collected during the discharge tests of the wells are analysed to determine the type of fluids encountered in the reservoir as to its alkalinity and/or ph, salinity, chloride or sulphate waters and its dissolved solids. When atmospheric chloride are calculated back to reservoir conditions, reservoir chloride concentrations could be obtained in all wells which can be compared to all other hot springs associated within the same reservoir. With the use of geothermometers, subsurface temperatures are predicted and compared with measured temperatures. The conformity of the chemical geothermometers can also be established with respect to the actual measured temperatures and therefore the equilibrium state of the reservoir. Geothermometers higher than actual measurements indicate that the well is probably located in the outflow zone, whereas geothermometers lower than measured temperatures indicate well fluids are being mixed with cold fluids during migration from the main upwelling zone to the outflow zone.

2.7.1 Discharge gas chemistry

Approximately more than 99% of the gas discharges from the wells are CO2 and H2S. High gas content in geothermal discharges are undesirable primarily because it is (a) often the cause of calcite scaling in the wells (b) imposes additional parasitic load from the power plant through the extraction of gas from the condenser, either by gas compressors or gas ejectors and (c) poses additional constrains on the degree of gas emission to the environment through the installation of high cooling towers for dissipation. Gas trend during production also indicates whether the gas produced at the surface is related to deeper reservoir conditions or just accumulation from the top of the reservoir due to the boiling of the reservoir with time, e.g., declining gas content with time. Degassed fluids indicate that wells are drilled in the outflow regions while high gassy wells are mostly found near the upwelling zone of the field.

2.7.2 Scaling and surface formation of scale

The most common forms of scaling in geothermal wells, pipelines and formations are calcite and silica. Calcite deposition is commonly associated with dilute alkaline-pH geothermal reservoirs, with high gas contents in relatively low reservoir temperatures (e.g., < 200°C). Calcite scaling within the wellbore of a discharging well can cause significant declines in mass flow as it plugs the wellbore. If this occurs, regular workovers to remove the deposition or alternatively, antiscalant chemicals are injected below the flashpoint in the wellbore, through downhole capillary tubing to prevent calcite scaling from occurring. The use of antiscalant chemicals has been the practice in the Philippines and found to be very successful in mitigating calcite scaling. However, the logistics and the cost of chemicals, and surface and downhole set up could be significant with reservoir monitoring posing a great challenge.

Silica (SiO2) deposition can also pose a significant problem in high temperature geothermal fields especially in the pipeline and reinjection wells. High temperature fluids have a higher amount of dissolved silica and therefore more readily deposit silica when separated or cooled below reservoir temperatures. The usual approach to controlling silica supersaturation is to design the fluid collection and reticulation systems to operate at a steam/water separator pressure at which saturation with respect to amorphous silica is not exceeded and to modify the pH of the geothermal fluid. In the Philippines, silica scaling has been manageable when the amorphous Silica Saturation Index is about 1.1 to 1.3.

The Philippines is now in an advanced stage of making use of silica inhibitors to deter silica precipitation in the wellbore and is thus able to reduce the acidizing and workover jobs on reinjection wells.

2.7.3 Acidity of geothermal fluids

Acid fluids impose significant constraints on the development of a geothermal field for power generation due to corrosion, which can be a major safety issue as it can cause major damage to well casing and surface pipelines, and scaling. The occurrence of acid fluids can be predicted from the composition of hot springs and solfataras in the surface. Acid feed zones in the well could be identified during drilling and therefore have to be isolated at once to prevent the zone from contributing during the discharge.

Acid fluids are considered as roadstoppers, and areas with significant acid fluids found in surface thermal manifestations were given low priority during the early years of geothermal development. However, recent developments indicate that acid fluids could be confined to some structures connected to the main high temperature zone and may not be as pervasive as initially contemplated. They can be excluded from the targets in the field and during production, as the steam cap expands and reaches the acid corridor in the field, the brine dries out and steam is produced. Several wells exhibiting acid fluids in the Philippines have been found to turn neutral after boiling propagates in to the reservoir. In Costa Rica, acid chemical inhibitors for corrosion are being used to neutralize the acid fluids to a manageable level.

2.7.4 Interpretation

The geochemistry gives rise to a hydrological model that indicates the sources and temperatures of geothermal water and of the various wells and hot springs to which they are associated. Shallow aquifers and deep seated fluids could also be determined. On the other hand, the isotope data suggests whether the sources of hot spring waters and the dwell discharges is common or of different origins. Here, the Giggenbach Geoindicator Ternary Plot demonstrates the relationship between those of the wells drilled and other springs found in the geothermal system.

2.8 Revised conceptual model

Based on the results of the detailed analyses of the data obtained from the exploration surveys and the drilling program, a revised exploration (conceptual) model is developed featuring more or less the different anomalies delineated by the combination of geological and MT/TEM geophysical surveys, and distribution of surface thermal manifestations supported by discharge output and chemistry of the various wells (Figure 4).

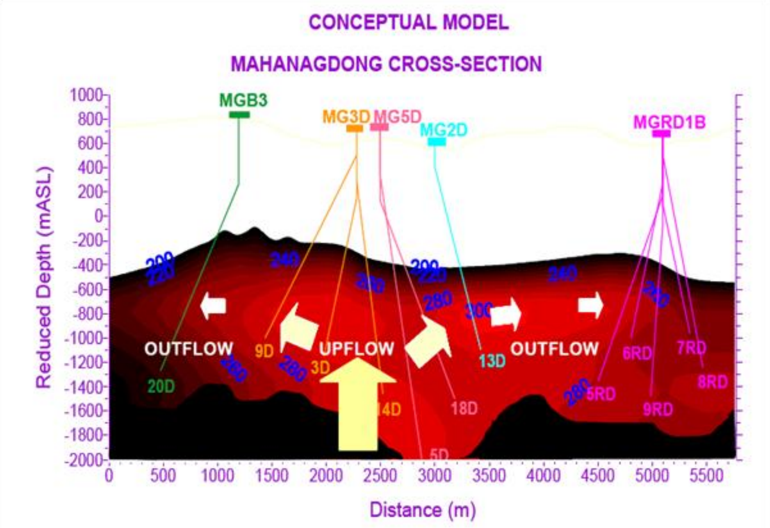

FIGURE 4: A typical conceptual model of the field showing the upwelling and outflow zones.

2.9 Resource sizing by simple analogy and volumetric reserves calculation

A number of approaches are available to assess the potential of a geothermal field. This includes a simple analogy with existing fields using power density estimations, stored heat calculation and through to a full three-dimensional numerical field simulation. Selection of the method is heavily dependent on the stage of development and the quality of data available for assessment. The first method is a very rough approximation of what is expected of the resource based on the preliminary surface exploration and drilling data; whereas the stored heat calculation using the Monte Carlo simulation is usually used in both an early stage, and after completion of drilling exploration stage. Power density estimates in the Philippines yielded 29 MW/km^2 for Tongonan, 18.5 for Tiwi, 34 for Makban, 9.7 for Mahanagdong, 9.8 for Mindanao and 7 MW/km^2 for Northern Negros. (Sarmiento and Bjornsson, 2007).

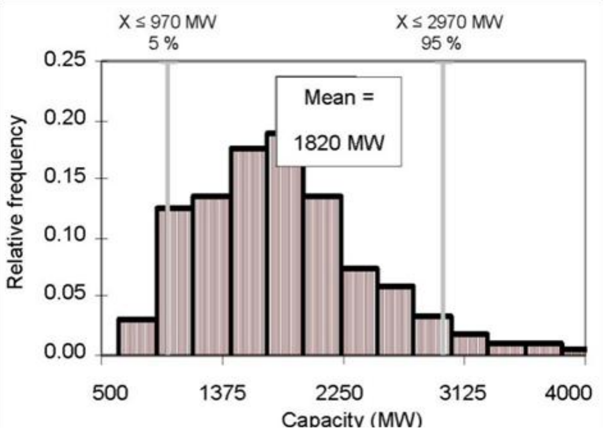

FIGURE 5: Relative frequency plot of volumetric reserves estimation of the Hengill geothermal field
(After Sarmiento and Bjornsson, 2007)

In the accelerated geothermal development in the Philippines, where power plants are required to be built as soon as a discovery well is drilled, the application of volumetric estimates in determining the initial capacity of the plant to be constructed has been very practical and reliable. Sarmiento and Bjornsson (2007) also discussed in detail the various applications of volumetric estimation and numerical modelling in the Philippines and Iceland to demonstrate the reliability of both techniques. The authors also showed that the development strategy of drilling only two to three deep exploratory wells satisfies the need in committing a minimum plant capacity of a geothermal field. Figure 5 is a frequency plot of the reserves estimation obtained by using a Monte Carlo simulation for the Hengill geothermal field in Iceland. The only reliable method that could be applied during this early stage is the volumetric heat assessment; very few wells were drilled and production data were limited to warrant the conduct of numerical modelling. The numerical modelling approach is usually the most appropriate and acceptable method for resource assessment, but usually data are so scarce during the development stage, that this is only preferably used when there are available historical data in which the forecast is able to be calibrated.

2.10 Numerical modelling

Numerical modelling is the mathematical representation of the physical state of the reservoir or the geothermal system. It draws from the interpretation of the various surface and subsurface physical and chemical measurements across the field. An outline of the reservoir defining the physical properties of the rock and the fluids is usually represented through the plan view and vertical section highlighting the peculiar features of the system e.g., temperature and pressure distribution, inferred permeability (primary and structures/faults), flow direction, heat sources and sinks etc. Numerical modelling in the Philippines is commonly applied when faced with the following major decisions:

- To formulate a management strategy requiring a change in the reinjection strategy
- To optimize the power potential of the field
- To determine the number of M&R wells to be drilled in the future to sustain the plant output

The first simulation work in the Philippines involved the natural state modelling of Tongonan geothermal field by Aunzo et al., (1986). This model had been expanded to include the matching of the production stage of the field (Salera and Sullivan, 1987); and later into forecasting as a management tool, to predict future reservoir performance and re-evaluate earlier estimates on the fields' generating potential under current generation and the future expansion level (Aquino et al., 1990; Sarmiento et al., 1993).

The results of the above-mentioned simulation studies and the 10 year stable performance of Tongonan I triggered an optimization study by Aquino et al (1990) and Sarmiento et al (1993). The latter simulation was to study field sustainability at pressures higher than a turbine inlet pressure of 0.55 MPa. The motivation was to increase plant efficiency while reducing steam consumption; hence, the total field mass withdrawal and pressure decline. The modelling study concluded that the field could operate at 1.0 MPa wellhead pressure for another 25 years provided that make-up wells are drilled. Figures 6 demonstrate the mass withdrawal resulting from increased power generation in the field while Figure 7 depicts the pressure response across the field as a result of this increased mass withdrawal. To date these sectors are still able to sustain production as projected with accompanied drilling of M&R wells. If the high pressure is not sustained in the future, it would be addressed by retrofitting the power plant. The Tongonan I turbine inlet pressure was consequently raised and the field capacity was optimized by installing a topping turbine (Sarmiento et al, 1993).

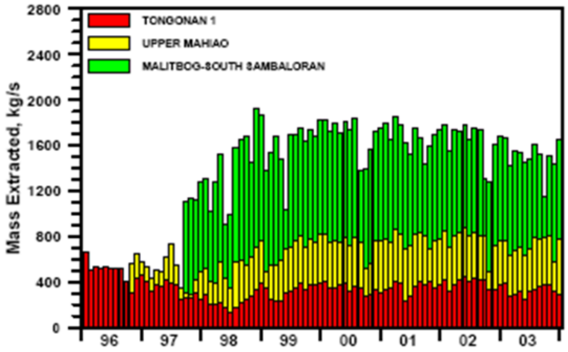

FIGURE 6: Plot of historical production from 1996-2003 with the commissioning of additional 600 MW in the Greater Tongonan Geothermal Field. (After Sarmiento and Bjornsson, 2007 and Aleman, 2005)

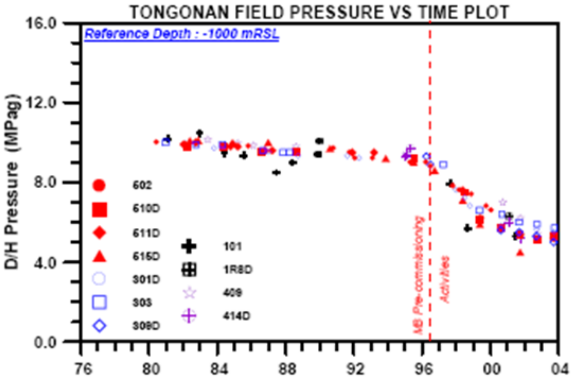

FIGURE 7: Plot of the downhole pressures measured from various wells in the Tongonan geothermal field showing the pressure response with increased mass withdrawal as a result of increasing field capacity.

The same study showed that Upper Mahiao and Malitbog could sustain 130 and 240 MW, respectively, for 25 years (Sarmiento et al., 1993) at the same high operating pressure of 1 MPa. It was further decided that the field generating potential could be raised by another 50 MW, via bottoming units in Malitbog and topping units in Tongonan I and Mahanagdong. These modelling studies led to the decision of raising the total generating capacity of Leyte power plants from the initial value of 112.5 to 700 MW in 1993.

All of these simulations had only one primary objective: to determine whether the field could sustain the initial committed capacity based on the volumetric estimation and find out the possibility of further expanding or optimizing the resource.

3. DEVELOPMENT OPTIONS

A resource evaluation would not be complete if the various scenarios by which the resource could be developed are not identified. The development options allow sensitizing the installation costs to determine the most economical way by which steam from the field could be produced. Development options relate to the various sites where production and the reinjection pads blow off stations, separator stations and power plant would be located. The distance of the pipelines and the total drilling depths of all the wells are all dependent respectively on their distance to the power plant and to the targets of the wells to be drilled. The cost of the pipes and the allowable pressure drops also determine the size of pipes to be used in steam conveyance to the separator and power plants. Smaller diameter pipes are cheaper but may mean higher pressure drops from the wellhead to the separator and power plant. A small diameter pipe and a lower pipeline costs should therefore be optimized against the ability of the reservoir to sustain any pressure drop on the system throughout the economic life of the plant.

Options for collaring the wells in one or multi production pads are commonly adopted depending on the topography of the area and access to the targets. The adoption of directional drilling allows wells to be drilled in multi cellar production pads and thus minimizes construction of sites, roads and erection of pipelines. The selection of the separator station and the reinjection pads should also accommodate gravity injection to avoid installation of booster pumps in injecting waste water. The size of the pipes area also evaluated considering the pressure drop that may be incurred from the well head to the separator station and to the power plant. Bigger pipes are laid down if the field is sensitive to pressure drawdown.

The location of the future M&R wells shall also be identified during the development stage so that spaces and piping will be coherent with existing or adopted pipeline design.

TABLE 1: Rundown of the steamflow and number of production and reinjection wells at various plant sizes.

Nominal power plant capacity	Nominal plant steam demand	Required number of production wells	Nominal brine flowrate	Required number of injection wells
(MWe gross)	(kg/s)		(kg/s)	
5	10.5	1	25	1
10	21	2	50	2
15	84	3	75	2
20	42	4	100	3
50	105	10	225	6
100	210	20	550	14

Table 1 shows as an example the number of production and reinjection wells at various development options based on the sizes of the power plants that could be installed in a given field. While it is obvious that larger size plants are cheaper to install and operate, a combination of two smaller units against one same size capacity unit may be more practical and even economical if all operational and market conditions are considered.

The resulting costs of the single and/or various combinations of these options will dictate which option may have to be adopted for that of the final field development. The type of power plants to be installed may vary from back-pressured to condensing steam turbines. In some cases, field development starts with constructing modular plants of 1.5 MW or 5 MW of non-condensing turbines, to be followed by larger size turbines when enough information on the resource characteristics have been obtained from the utilization of the modular plant.

Other generation options like the binary cycle technologies in combination with standard steam turbines are used to optimize power generation. A binary plant makes use of the separated brine produced from the field that is normally injected back to the reservoir. In some cases, a combined cycle geothermal power plant unit utilizes the exhaust steam from a high pressure turbine to heat up the binary fluid that is used in the organic cycle power plant.

4. CONCLUSIONS

The key elements vital to the successful evaluation of a geothermal resource consist of a thorough review of the exploration results, well discharge tests and application of the appropriate reserves estimation and numerical simulation techniques. The size and the quality of the reservoir fluids define the various options to be followed in planning for full commercial development of the field. The well chemistry takes special emphasis on scaling potential, acidity, high salinity and gas content of the reservoir. These parameters imposed constrained the development of the field since additional equipment are needed to be installed to mitigate their negative effects on well production, frequent maintenance on surface facilities and increased gas emission to the environment. Calcite and silica scaling are still considered the most common problems in geothermal development but recent technologies are developed that inhibit their formation in the wellbore and the reservoir. A more reliable estimation of the size of the reservoir is necessary to minimize risks on over exploitation that would impact on the viability of the project in the future. Volumetric modelling is applicable when only fewer wells are drilled and when small size power plants are being contemplated for initial development. When production history becomes available and more wells are distributed in the field, a numerical simulation would be the best method to predict future production and sustainability of the field. Numerical simulation has proven to be very useful when optimizing the capacity of the field especially when calibrated from a long record of production history as applied in many geothermal fields in the Philippines. The need to identify development options exist in determining and sensitizing the most economical way of producing the steam in a given field.

REFERENCES

Aleman, E.T., Sta Ana, F.X.M., Saw, V.S., Esberto, M.B. and Canete, G.F., 2005: Steam Supply Sharing Through Steamline Interconnection – The Tongonan Geothermal Field Experience, Philippines, *Proceedings World Geothermal Congress 2005*.

Aquino, B.G., Sarmiento, Z.F., Aunzo, Z.P., Sarit, A.D. and Rodis N.O., 1990: Simulation of Two Exploitation Scenarios for Further Development of the Tongonan Geothermal Field. Report for UN-DTCD Project PHI/86/006. New York.

Aunzo, Z. P., Sarmiento, Z.F. and Sarit, A.D., 1986: Simulation of the Tongonan Geothermal Field, The Initial State. *Preliminary Report, 8th New Zealand Geothermal Workshop, 1984*. p. 135-140.

Delfin, F.G.J., Layugan, D.B., Reyes, A.G., Parilla, E.V. and Salera, J.R.M, 1992: Mindanao I geothermal Project: Surface Exploration, Deep Drilling and Preliminary Reserve Estimation, Journal Geological Society of the Philippines, 47. p. 107-119.

Salera, J.R.M. and Sullivan, M.O.J., 1987: Computer Modelling Studies of the Tongonan Geothermal Field, *Proceedings: 9th New Zealand Geothermal Workshop, 1987*. p. 169-178.

Sarmiento, Z.F. and Bjornsson, G., 2007: Reliability of Early Modelling Studies for High Temperature Reservoirs in Iceland and the Philippines. *Proceedings, Thirty-Second Workshop on Geothermal Reservoir Engineering. Stanford University, Stanford, California, January 22-24, 2007.* SGP-TR-183

Sarmiento, Z.F., Aquino, B.G.,Aunzo, Z.P., Rodis, N.O., and Saw, V.S., 1993: An Assessment of the Tongonan Geothermal reservoir, Philippines at High-Pressure Operating Conditions, *Geothermics, 22.* p. 451-466.

Siega, C.H., 2007: Validation of Reservoir Simulation Study in Mahanagdong Geothermal field, Leyte, Philippines. *Proceedings: 28th Annual PNOC EDC Geothermal Conference. Makati, Philippines. March 7-8, 2007.*