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GEOTHERMAL RESOURCE ASSESSMENT – VOLUMETRIC RESERVES ESTIMATION AND NUMERICAL MODELLING

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ABSTRACT

Volumetric reserves estimation and numerical modelling are the two most commonly applied methods in geothermal resource assessment. During the early stages and when accelerating the development of an area, volumetric method is considered to be the most practical approach. It is applied to evaluate a resource that was drilled with only 2-3 wells with a reasonable degree of certainty. It does not neither predict entries and effects of cold fluids, acid fluids, and mineral deposition; nor is the possible recharge of hot fluids underneath the reservoir taken into consideration. There is no doubt that numerical modelling is still the best approach in conducting resource evaluation. However, it needs more detailed knowledge of the reservoir parameters to be assigned to the various cells in the numerical grid to be reliable. This information is not always available during the early stages of development, and the field developer is required to wait for wells to be drilled and tested, before an appropriate model that truly represents the physical state of the reservoir can be made. Moreover, boundary effects are usually not observed during the early stages of production, and the initial modelling results usually appear to be more pessimistic than the final runs; hence, the models need to be calibrated several times to make a production forecast more acceptable. Some of the applications and limitations of these two methods are discussed in this paper.

1. INTRODUCTION

Geothermal 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. An assessment of geothermal resources can be made during the reconnaissance and exploratory stage prior to drilling of wells, taking into account the extent and characteristics of the thermal surface discharges and manifestations, geophysical boundary anomaly, the geological setting and subsurface temperatures obtained from geothermometers. The normal feature of this study is the presentation of a conceptual or exploration model of the area that mimics the source of heat and the probable host of the geothermal reservoir. It also serves 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 a resource assessment to refine and revise the preliminary conceptual model based on the results of downhole measurements and observations from drilling. It quantifies the proven amount of heat (reserves estimation) that can be mined for the economic life of the plant, usually 25 years. An updated resource assessment can be made after drilling a number of wells and after the wells have been put into production for forecasting the future performance of the field. When planning to expand the capacity of an operating field, a resource assessment describes the overall production history. It shows if additional reserves may be available to supply supplementary steam to the power plant. A resource assessment or reserves estimation could also be used for formal booking of geothermal energy reserves, for accounting purposes or annual reporting to shareholders or portfolio management (Sanyal and Sarmiento, 2005). This report is intended to enhance the company valuation when presenting to institutional investors for fund raising.

The need for a more reliable estimation of a geothermal reserve has been the desire of many steam field developers around the world, especially with the increasing cost of putting up a power plant. There is also the need to secure environmental permits before a project can begin and this requires that the estimated resource potential is already indicated. It takes one or two years to be issued environmental clearance; therefore, one application that covers the entire field should be a very practical option. Emphasis is given to the policy on sustainable production as an environmental requirement, one that would preserve the resource for the needs of future generation. The reliability on geothermal reserves estimation, therefore, cannot be ignored. Sarmiento and Bjornsson (2007) discussed the reliability of both the simple volumetric models and the sophisticated numerical modelling techniques. The use of simple volumetric calculation in initially committing a power plant capacity in the Philippines has since proven that it can reliably predict the minimum commitment for a field even with only two or three discovery wells drilled. On the other hand, numerical modelling provides for a portfolio of management strategies, because field performance can be predicted under various scenarios. However, the results of numerical simulation are heavily dependent on the available number of wells, usually very little at the time the size of the power station has to be determined. Furthermore, Sarmiento and Bjornsson (2007) indicated that the amount of recharge from the sides and the bottom of the reservoir are usually observed only during the later period when there is already a significant pressure decline. If this condition needs to be inputted in the estimation, it means delaying the project for a number of years because long term testing of production wells need to be done to produce such results.

This paper presents examples of some geothermal fields that were assessed using volumetric calculation and numerical modelling. Discussions on the performance of these fields are included to highlight the reliability of the two techniques.

2. PHILIPPINE DEVELOPMENT STRATEGY

With the results of advanced exploration activities in 22 distinct resources in the country, a general pattern in the strategy is being followed (Barnett et al, 1984). The stages of sequential level of investigating geothermal resources consist of the following:

- Regional identification of prospect areas
- Geoscientific prospecting methods
- Exploration and delineation well drilling
- Resource assessment

The regional identification of a prospect is carried out 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 spotted and identified in 25 volcanic centers as hot spout, mud pools, clear boiling pools, geysers, and hot or warm altered grounds (Figure 1).

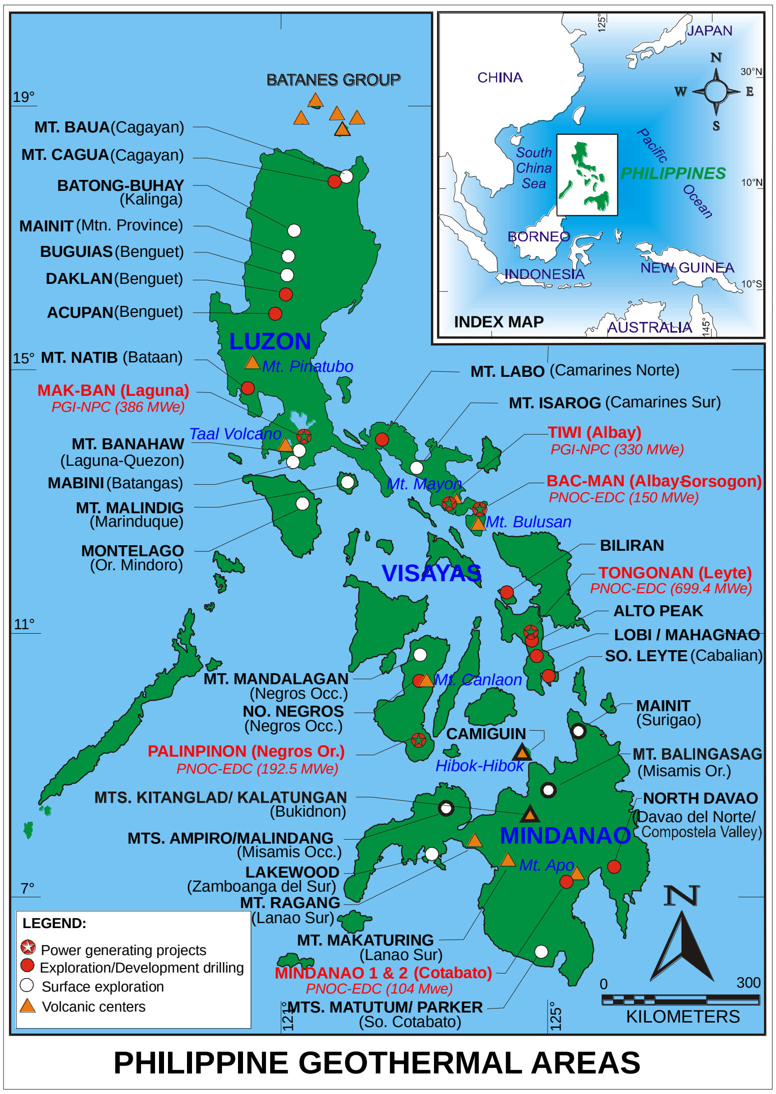

FIGURE 1: Map showing the geothermal areas in the Philippines

Geoscientific prospecting commenced following the identification of a more potential resource area by conducting surface geological mapping, geochemical sampling and geophysical measurements. 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.

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 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 basis for building the 2 x 52 MW power station (Figure 2).

3. VOLUMETRIC RESERVES ESTIMATION

Volumetric reserves estimation, also known as "stored heat calculation", quantifies the thermal energy in-place of a given volume of rock. The calculation of the volumetric heat is done based on certain criteria which are obtained from direct and indirect measurements on the physical properties of rocks and the geothermal fluids. The degree of certainty of the estimate increases with increasing number of

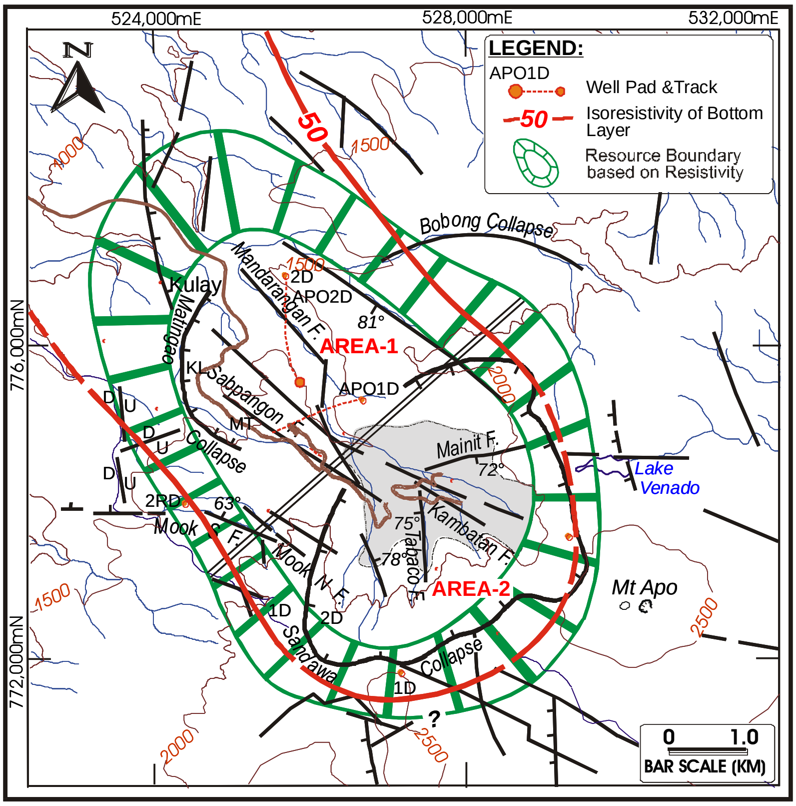

FIGURE 2: Exploratory well location map showing provisional resource boundary for Mindanao geothermal field. (Modified from Delfin et al, 1992)

wells, consistent with the number of blocks or the area of influence for each well. The volumetric method does not account for the quality of fluids (acid and cold fluids) that could be encountered during production. The rapid communication between production and reinjection wells could cause for an irreversible cooling of production wells that would lead to shutting down of affected production wells; therefore, the drawback is that the reserves may be overestimated. On the other hand, it also does not take into account the amount of vertical or lateral recharge which could replenish the reservoir fluids during production; therefore, the reserve estimate may be understated. The reservoir dynamics are not initially considered in the estimate but are sensitized through numerical modeling.

Table 1 shows reserve estimates for various geothermal fields in the Philippines, based on volumetric methods. The different figures are taken from various reports and papers, and are mentioned in Sarmiento and Bjornsson (2007). After successfully confirming the commercial viability of Tiwi, MakBan, Tongonan and Palinpinon, the country's exploration and development strategy had to be revised by reducing the number of exploratory wells to half, from 4-6 to 2-3 wells. Drilling of thermal gradient or shallow exploratory holes from 300-900 meters was also discontinued. It had been shown that these shallow holes could not capture the signatures of the upwelling zone, the premium location for drilling targets; frequently, only the high temperature gradient from the outflow zones are intersected, giving false hope on the location of the upflow.

The development of Tongonan I was committed after successfully drilling the first discovery well 401; the reserves estimate of which was calculated at 3000 MW-years, equivalent to 120 MW for 25 years (Imrie and Wilson, 1979). A pilot plant with a 3 MW capacity was subsequently commissioned 9 months after the first drilling began at Well 401 in October 1976.

At the time of decision to construct a 112.5 MW Palinpinon I plant, calculated energy reserves of the steam field had increased to 9000 MW-years or ~360 MW for 25 years (Maunder et al., 1982). The estimate was based on data obtained from 2 wells, Okoy-4 and Okoy-5 where temperatures of 299°C and 310°C respectively were observed. This capacity was seen as just the first stage in the field development. The second stage development involved the installation of 4 x 20 MW units in three separate sectors consequently, putting the total capacity in the field at 192.5 MW. The installed capacity remains lower than the reserves estimate because of the problems associated with rapid reinjection returns, which now shows that an additional 20 MW could be sustained by the reservoir in the next 25 years.

TABLE 1: Initial reserves estimates on various fields in the Philippines, based on volumetric models (Modified from Sarmiento and Bjornsson, 2005).

Year	Field	Area (km2)	Installed Capacity (MW)	Reserves (MW)	Comments
1978	Tong-I	-	112.5	120	3 MW on-line
1980	Mahiao-Malitbog	5-22	132 245	720-1000	112.5 MW-on-line
1982	same	same	377	400-570	Lower Temp.
1982	Maha-nagdong	-	180	138	2 wells
1988	same	-	same	138	3 wells
1990	same	-	same	80-109	conservative
1991	same	9.8	same	107-167	3 wells
1992	same	6-10	same	100-180	Monte Carlo
1978	Pal-I/II	11	192.5	360	2 wells
2005	Pal II	-	80	100	20 MW opti
1982	BacMan I and II	-	150	160	Feas. Study
1985	same	12	same	150	
1992	Mind. I	8	52	117-220	2 wells
1992	Mind. II	8	54	175-328	-
2001	N.Negros	6-9	49	42-63	4 wells

In the Mt. Apo geothermal field, the development was done in two stages; firstly in Area 1 where two wells were drilled and secondly in Area 2 where the hottest part of the geothermal system was postulated to exist (Figure 2). The first stage 52 MW unit was installed in Area 1 followed by another 52 MW unit in Area 2 after confirming the postulated model of the system. Some delays were encountered in the stage 2 development because of concerns on the intersection of acid fluids in some wells.

Several estimates were made in Mahanagdong field in the Greater Tongonan geothermal field from 1982 to 1992. These estimates were based on the deterministic approach which assigns a fixed value to all the reservoir parameters, and the Monte Carlo simulation, which uses the uncertainty distribution or range of values in some parameters. The earlier estimates using the deterministic approach showed the capacity to be only 138 MW based on 2-3 wells; however, the Monte Carlo simulation suggested the capacity to be at a minimum of 100 MW and possibly 167-180 MW at the most. This is equivalent to a power density of 18 MW per square kilometre. For comparison, we calculated power densities from installed capacities and resource areas reported for the various fields in the Philippines. This yielded 29 MW/km^2 for Tongonan, 18.5 for Tiwi, 34 for Makban, 9.8 for Mindanao and 7 MW/km^2 for Northern Negros.

4. 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 the field
- To determine the number of M&R wells to be drilled in the future to sustain the plant output

TABLE 3: An overview of detailed reservoir modelling studies in the Philippines (After Sarmiento and Bjornsson, 2007)

Field	Year	Area (km^2)	Generat Capacity (MW)	Comments
Tongonan	1986	16	112.5	First simulation (CHARGR)
Tongonan	1987	60	112.5	MULKOM
Tongonan	1990	50	112.5	Development strategy expansion
Tongonan	1992	50	112.5	Optimization
Tongonan	1999	-	500*	Tedrad forecasting
Maha-nagdong	1993			Nat. state MULKOM
Same	2002		200	Field Mgt. TETRAD
Palinpinon I/II	1990	650**	112.5	MULKOM Forecasting
Mindanao I/II	1995			First detailed modelling
Mindanao II	1996			Detailed model expansion

*Excludes Mahanagdong ** Extended Recharge Block

Table 3 gives an overview of various detailed modelling studies conducted so far in the Philippines. 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 future expansion level (Aquino et al., 1990; Sarmiento et al., 1993). Other simulation works were conducted for Palinpinon in cooperation with Lawrence Berkeley Laboratory and United Nations/Department for Technical Cooperation and Development (Amistoso et al., 1990). Urmeneta (1993), Sta Ana et al. (2002) and very recently Siega (2007) dealt on the modelling of the Mahanagdong sector of the Greater Tongonan geothermal field; while Esberto (1995) and Esberto and Sarmiento (1999) discussed the results of the numerical modelling in the Mindanao geothermal field. 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.

4.1. The Tongonan Geothermal Field

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. 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).

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.

4.2. The Mindanao Geothermal Field

Figure 3 shows the numerical grid used in the detailed modelling studies for Mindanao. The preliminary objective of the study was to evaluate the sustainability of the field under the operating scenario existing after the 1996 commissioning of the first 52 MW power plant. Other studies dealt with the impact of the brine return to the production sector once the field capacity is expanded by 50-70 MW on top of the existing 106 MW in Mindanao I and II. The model considered a total area of 60 km^2extending vertically from an average topographic surface of +1250 to -1500 m MSL; divided in 6 layers with a total of 1,122 blocks.

The results of the predictive modelling indicated that the 17 wells drilled to supply the two power plants for 106 MW could sustain the output for 5 years, requiring an additional M&R well on the 6th year (Figure 4) This was a good measure of how the field will behave and gave confidence on the original assessment of the area. The predicted decline rate was about 50 t/h, equivalent to 10 t/h per year or about 1 MW per year, roughly 1 % decline rate per year.

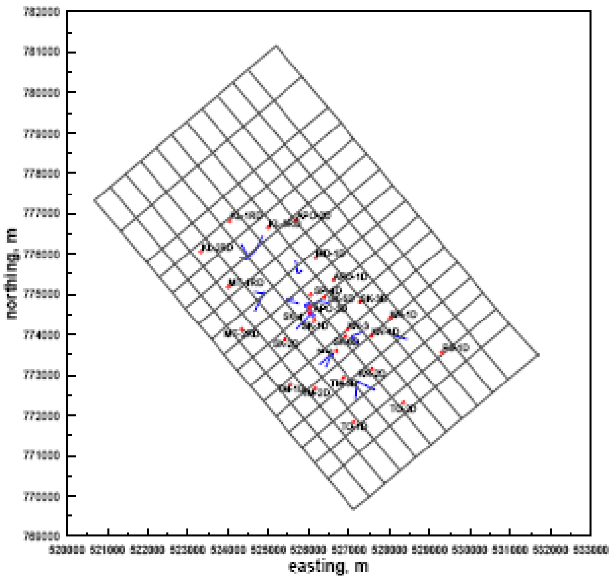

FIGURE 3: The grid adopted for the Mindanao numerical modelling studies (After Esberto and Sarmiento, 1999).

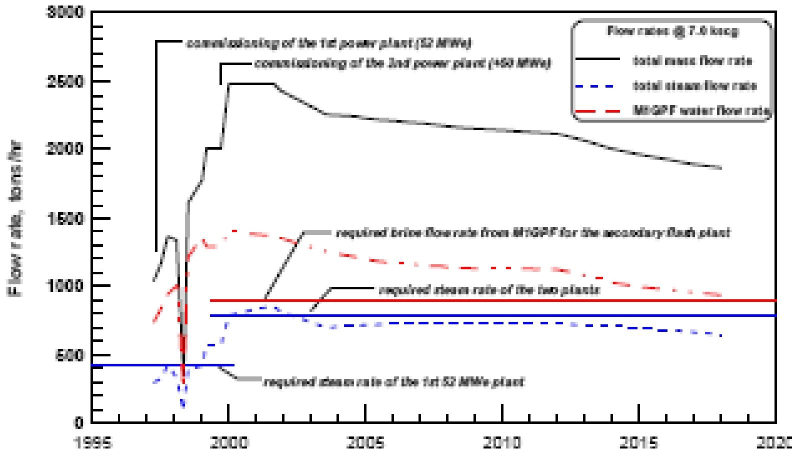

FIGURE 4: Results of the Mindanao performance forecast.

4.3. The Mahanagdong Field

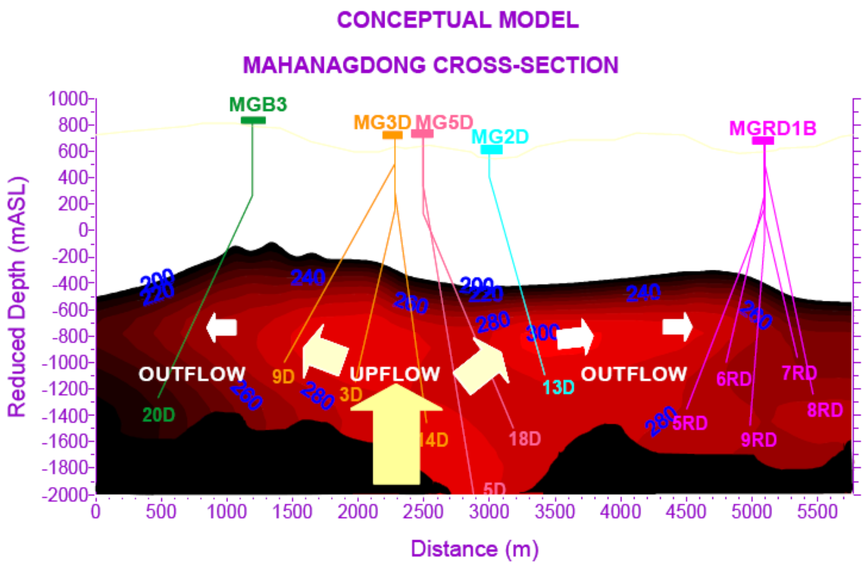

FIGURE 5: Conceptual model of the Mahanagdong geothermal field (After Siega, 2007).

The most significant simulation studies conducted in Mahanagdong was reported by Siega (2007) where the negative effects on the migration of hot fluid and condensate injection, as well as the shallow meteoric cold waters, were addressed. Mahanagdong field was commissioned in 1997, and four years later had exhibited large pressure drawdown because of the close spacing among the production wells. The rapid pressure decline caused the peripheral cold waters to migrate to the western part of the field. As a consequence, cooling of some production wells ensued, and led to a reduction in output from the wells. The study further revealed that future outlook in the steam supply could be improved by modifying the injection strategy. The changes involve the relocation of condensate injectors and the utilization of one hot injector close to the production wells to balance and mitigate the relative fast movement of peripheral cold waters in the western portion of the field. The results of the current performance of the wells previously affected by these cooling waters showed significant improvement in output. The overall steam supply of the field, likewise, signified the importance of the simulation studies (Figure 5).

4.4. The Palinpinon and the Bacman Geothermal Fields

The stable performance of Palinpinon despite the effects of reinjection returns need not require a follow-up study on the Palinpinon modelling. Fast reinjection returns have been of concern in Palinpinon (Macario, 1991). These are managed by revision of conceptual reservoir models; revisions that are based on field studies like tracer tests, chloride level monitoring and relocation of injection sites. The same is true for Bacman, where power generation has never been maximized because of associated problems with the power plant since it was commissioned.

4.5. Detailed Modeling in Iceland

Unlike the accelerated development strategy in the Philippines, the Icelandic geothermal industry has practiced a step-wise development strategy for their high-temperature resources. This means that power station capacity starts from a very conservative level expanding only after many years of continuous production. Power plants are built only after drilling of 5-10 full size production wells and months to years of flow testing. Development of 3-D numerical reservoir models is held hand-in-hand with field activities, resulting in frequent mesh expansion and recalibration phases. This account in particular for the Hengill model (Figure 6), which has been maintained and recalibrated for 18 years (Björnsson et al., 2006). The main difference between the Iceland step-wise development and the Philippines accelerated development program is that there would be a greater need for drilling M&R

wells in the latter approach. Make–up drilling is unheard of in Iceland because well pressures are 5-20 bars higher than the separator and turbine inlet pressures. Recharge from the boundaries has been sufficiently large. The Icelandic tradition of conservative generating capacity estimates has recently shifted priorities in steam field management from stabilizing field outputs to that of expanding. New units are now added to existing plants.

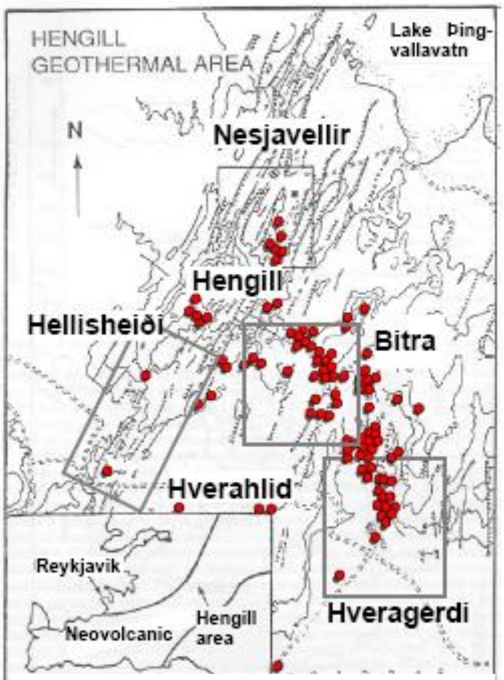

FIGURE 6: The Hengill geothermal field in Iceland (After Bjornsson,2006)

The results of early numerical modelling in Iceland also showed that previous predictions on the field capacities are pessimistic, and brought about by the initial dominance of the single phase fluid behaviour. With a single phase fluid acting in the reservoir, pressure draw-downs are relatively high. When the steam cap and two-phase fluids expand, constant pressure behaviour dominates the discharge and increased capacities are obtained. This is best exemplified by Svartsengi on the Reykjanes Penisnula in Iceland.

Moreover, the Krafla geothermal field in Northern Iceland was calibrated against a few years of production data. The resulting generation was rather low (50 MW). Like the Hengill field, it is liquid dominated but with temperatures lying within the BPD curve. Under these conditions, the pressure draw-down and enthalpy data generally lead to low reservoir permeabilities, until better boundary pressure impacts the reservoir late in the production period. Hence, adjustments are made and higher capacities are obtained after the model is calibrated.

In general, losing significant economic benefits may be the outcome of the Icelandic approach as a result of capacity underestimation, while waiting for the field to assume the more inherently long term field characteristics before tapping the optimum output.

4.6. General Numerical Modelling Results

One of the most revealing results conducted in most of these fields in the Philippines concerns the heat and mass extraction recovery from the reservoir. The results of the simulation for Tongonan was to generate 112.5 MW for 25 years yielded with a recovery factor of up to 28% if there is reinjection of geothermal brine within the well-field; and up to 32% without reinjection (Bayrante et al., 1992). These figures are significantly higher than those obtained from Muffler and Cataldi (1978) with a recovery factor of 25% for the 8% porosity assigned for Tongonan. The assumed 8% porosity represents the value obtained from modelling the production history for Tongonan I.

The disparities in the reserves estimation shown in Table 1 are mostly due to the uncertainties in the porosity and recovery factors. An over estimation may bias porosities in the volumetric models. However, the results of these simulations indicate that porosities range from 6-10% in order to match flow enthalpies. Despite the unique characteristics and responses of each of the fields during production, considering results of the extensive studies and modelling of the fields in Table 1, a more congruent and consistent assessment using volumetric models is currently achieved.

It should be noted that total installed capacities approximate the initial reserves estimate for all the cases in Table 1. Exceptions are Palinpinon and Mindanao where problems on reinjection returns and presence of acidic fluids deter immediate expansion.

5. RELIABILITY OF RESERVES ESTIMATION

The issue on the reliability of reserves estimation is the main subject of the paper by Sarmiento and Bjornsson (2007). They pointed out that by following simple volumetric models most of the geothermal fields in the Philippines were developed closed to their optimum capacities. It has been more than 28 years now since MakBan was developed and to date is still capable of producing up to >400 MWe (Golla et al, 2006). Numerical modelling refines what could have been simple formulation of management strategies; identifying reservoir management portfolios that would render more technical and economical advantages. It gives confidence that the field output could be sustained over the economic life of the field.

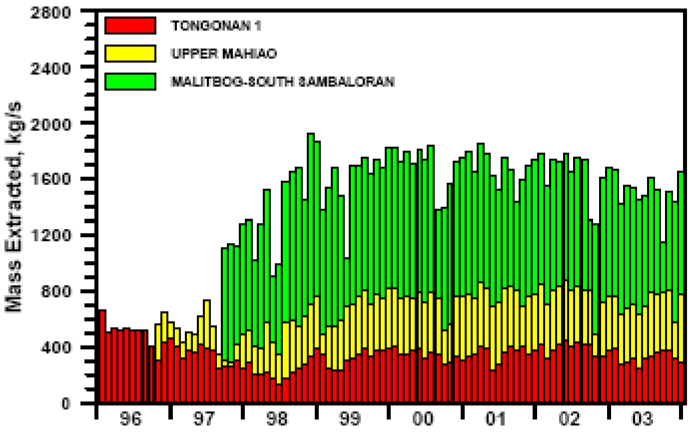

FIGURE 7: Annual mass extraction in the Tongonan geothermal field (After Aleman,2005)

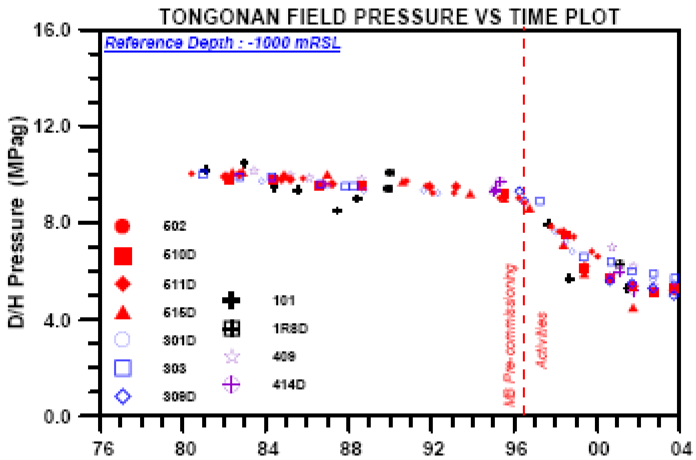

FIGURE 8: Pressure trend in the Tongonan geothermal field (After Aleman,2005).

Figure 7 shows the annual mass extraction data from the Tongonan geothermal field. The Tongonan I sector has been powering 3 x 37.5 MW units since 1983, producing 65-85 MW; Upper Mahiao with 125 MW and Malitbog 218-222 MW from 1997 to present. The significant withdrawal in the area caused rapid pressure drawdown (Figure 8), intense boiling and increase in enthalpy from the wells, accompanied by high total discharge of fine particulates in some wells. This was remedied by steam washing and solid entrapment pipe spools. It has been 25 years since inauguration of Tongonan I, and the numerical modelling forecast indicates production can continue for more than 20 years. The Upper Mahiao sector of the Tongonan field has been the source of excess steam partly being directed into the Malitbog and the Manangdong sectors. This started when Mahanagdong encountered steam supply problems due to: (a) reinjection returns and condensates from the power plant and (b) migration of cold surface meteoric waters as discussed above.

The Palinpinon field, which was commissioned in 1983, is still capable of producing 112 MW, and it could produce more power for the same mass flow if only the efficiency of the power plant could be improved. The most peculiar feature of the management strategy in this field is that additional wells had to be drilled in the area not as replacement production wells, but as replacement reinjection wells. Early in the life of the field, rapid interaction took place amongst the production and reinjection wells. Some production wells had cooled down irreversibly (Okoy 7 and PN-26), necessitating the transfer of most of the reinjection load to a more distant location. This strategy provides beneficial result in that the wastewater is allowed to travel at longer distance, and gets reheated along the way before returning with a sufficient temperature increase to the production wells. The reinjection returns act as a pressure support to the reservoir and has levelled the field pressures since 1992; 10 years after the commissioning of the power plant (See Figure9).

The Mt. Apo Geothermal Field has been in production for the last 10 years, and so far the field has been producing steadily without major reservoir concerns. There is a planned expansion of up to 50 MW in the field that would tap the high temperature resource near the upflow zone. This sector was originally characterized by acidic fluids; but has recently turned two-phase and is now suitable for commercial production.

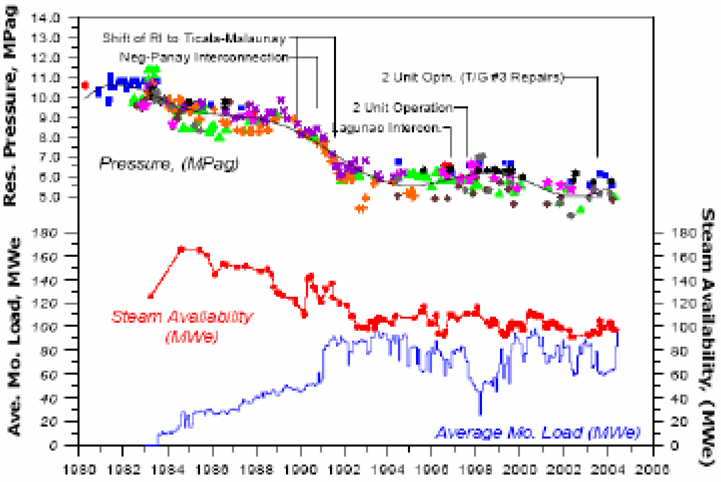

FIGURE 9: The pressure trend along with the available steam supply an average load in the Palinpinon geothermal field. (Aqui et al, 2005)

6. CONCLUSIONS

The experience from the Philippines is that volumetric estimation could be used to reliably asses the size of the power station suitable for commitment in the early stages of field development. Volumetric estimation has the advantage that it is not necessary to wait for the availability of long term production data usually needed in conducting a numerical modelling study. By committing part of a delineated resource after drilling 3 to 4 production wells, immediate utilization of the discovered resource is ensued. However, this can only be confidently carried out when all the reservoir parameters and flow test data available represent what an expert believes is the true reservoir condition. While numerical modelling is still considered to be the best approach to assess the long term performance of the reservoir, it is constrained by more detailed parameters covering the reservoir block, which in all cases need long term testing to make the reservoir boundary effects visible in the reservoir response. It is believed that by introducing some conservative values in the assumptions used in the volumetric estimation, overestimation of the size of the reservoir, which is an issue to most developers, could be avoided. Numerical modelling could then come in the later stages of field development to confirm the early volumetric estimates. Volumetric estimation would also be able to provide portfolios of management strategies the maximum technical and economical returns.

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