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Review of Generating Capacity Estimates for the Momotombo Geothermal Reservoir in Nicaragua

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Keywords

Momotombo, Nicaragua, performance, conceptual, volumetric, numerical, 3-D, management, scaling, possible, proven, resource, reinjection, reservoir, cooling

ABSTRACT

A proven 2 km², 1300 m thick and initially 240-320 °C Momotombo reservoir has reached a stabilized 32 MW_e generation after declining from a short peak of 60 MW_e to 9 MW_e in 1991 to 1999. The field operation has been troubled with scaling and lost enthalpies, mainly due to a 100-150 °C recharge from a constant pressure boundary. These difficulties have now been mitigated by mechanical workovers, calcite scaling inhibition, acid stimulation, commissioning of a binary unit and drilling of deep wells. For environmental concerns, Ormat also implemented full reinjection to avoid pollution of the Managua Lake done previously. Earlier volumetric models predicted generating potentials in excess of 100 MW_e. They presumed 2-3 times thicker and larger reservoir than seen in downhole data collected later. A numerical model, calibrated in 1994, suggested up to 150 MW_e generating capacity, largely from a hypothetical production zone at 1600 to 2600 m. As this model lacked the constant pressure boundary, it failed to predict enthalpy losses due to cold water invasion after 1991. Furthermore, the deep reservoir theory still needs to be confirmed. A later model, calibrated in 2005, includes the constant pressure boundary. It suggests a moderate generating capacity of 50 MW_e. As the current proven reservoir seems to be constrained by heat more than mass reserves, attempts to increase generation should be directed to greater depths, into a possible resource. Statistically, deeper layers have average well success of 2 MW_e and well output may decline by 5 % annually.

1. Introduction

The now 25 years operation history of Momotombo has been plagued with challenging resource and power plant

issues. Despite very dense drilling of 47 wells into 2 km² area, present generation has stabilized at only 32 MW_e. The installed power plant capacity is, on the other hand, 77 MW_e. A current mean well output of 0.75 MW_e is far below a world average of 1.9 MW_e/well (Stefansson, 1992). The Momotombo field and plant performance has therefore been and is still a source of disappointment and frustration. In particular since the actual output is substantially lower than indicated by older modeling studies. Ormat, the current field operator, therefore asked the author of this paper to review existing generating capacity studies on the Momotombo resource and come up with his own viewpoint on the current situation.

The following paper is structured as follows: After briefing on the conceptual reservoir model, field performance history is addressed. Existing volumetric models are reviewed and their predictions compared with actual drilling success and field performance. Two numerical model studies from 1994 and 2005 are also reviewed. In a discussion section some statistical parameters such as mean output per well, well success with depth and produc-

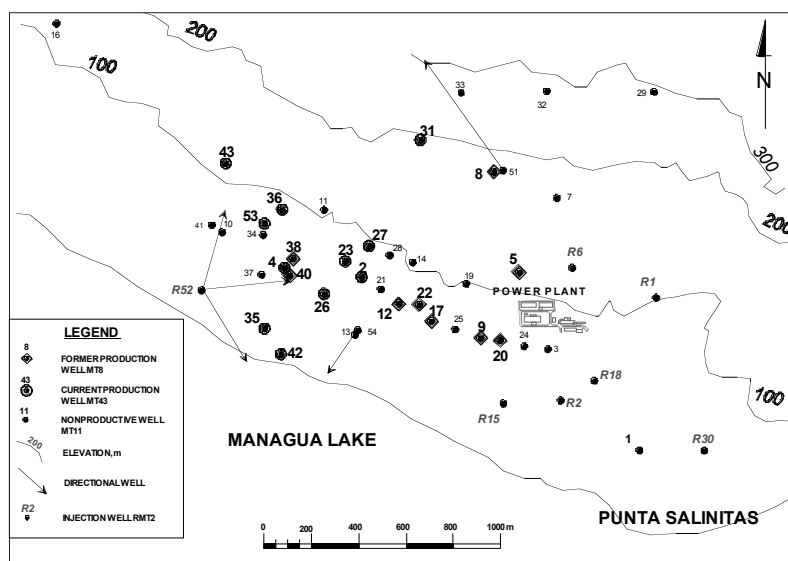


Figure 1. Momotombo well status and locations.

tion load in MW_e per km^2 of resource are evaluated and compared with other fields. Reasons for less than anticipated generation are addressed and means of increasing production suggested.

2. The Conceptual Reservoir Model

The Momotombo geothermal reservoir is hosted within sedimentary and andesitic volcanic formations that relate to the Momotombo volcano. To date 47 wells, ranging from 300 to 2900 m depth, have been drilled. Figure 1 shows these well locations. Figure 2 shows a temperature cross section from West to East. It clearly illustrates a hot ($240\text{--}320^\circ\text{C}$) and vertical upflow zone, as well as a shallow reservoir layer ($220\text{--}240^\circ\text{C}$). The shallow layer conducted deep fluids towards East, eventually to be discharged at surface near Punta Salinitas. Also worth mentioning is a cold ($100\text{--}150^\circ\text{C}$) fluid recharge from East, that appears to have been active in the natural state. Permeability is high in the shallow system and well success also while still hot. Quite many citations are available in the geothermal literature on the Momotombo conceptual reservoir model and its main features have remained intact for years (Porrás, 2005).

There are however a few items in the conceptual reservoir model that vary from one author to the other. In particular the existence of a brittle reservoir layer below ~ 1600 m depth (DAL, 1994). If true, the layer should be an important reserve in the long term field management. At this time, however, success of drilling deep in Momotombo is poor and undermines the hypothesis. Additional deep drilling by Ormat in 2000–2004 suggests, however, that there exist vertical and permeable faults and fractures in the Western wellfield that govern fluid flow in the area. Their strike appears Northerly. Finally, recent drilling activities have shown that commercial permeability is not encountered when drilling south, in under the Managua Lake.

3. Field Performance History

Figure 3 shows power generation and cumulative number of wells in Momotombo, from commissioning of the first 35 MW_e single flash unit in 1983 until present. A second 35 MW_e unit came on line in 1989 and a 7 MW_e binary unit in 2003, bringing installed capacity to the current 77 MW_e . The figure illustrates numerous difficulties faced in the Momotombo plant and resource management, most often resulting in declined generation rates. For example, the second 35 MW_e unit was out of operation most of 1988 to 1989 due to shaft vibrations. A gradual decline in total generation is evident after 1991. It relates to enthalpy loss of shallow wells to the East. To worsen the situation, some of the shallower and intermediate depth wells in center wellfield began to develop calcite scaling plugs after 1996 (Porrás, 2005). Unfortunately, make-up drilling of wells 38 to 43 in 1992 to 1997 failed to counteract the generation loss. The current mean well success is sitting and painfully low $0.75 \text{ MW}_e/\text{well}$.

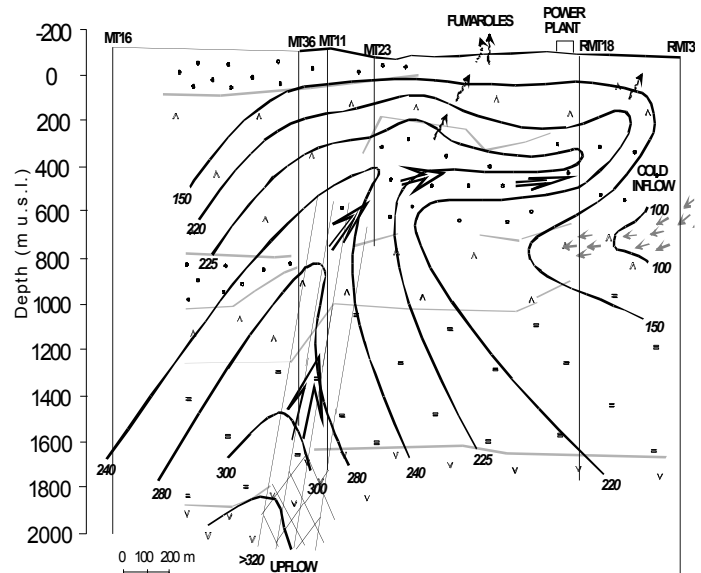


Figure 2. A temperature cross section from W to E.

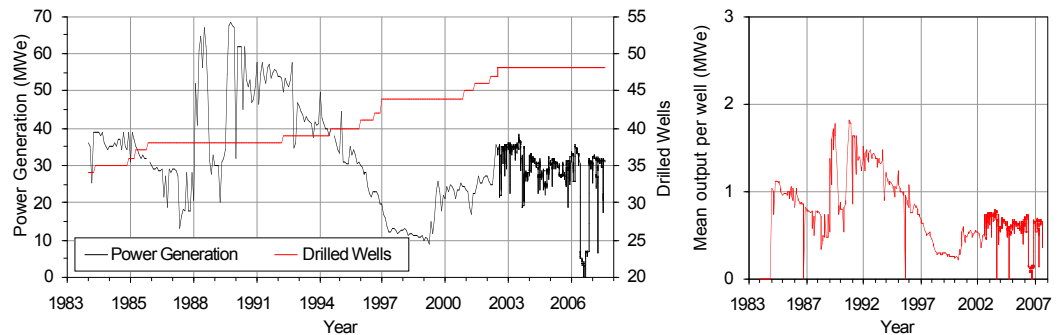


Figure 3. Power generation history, total well number and mean electrical output in Momotombo.

When Ormat overtook the Momotombo project in July 1999, the total generation was only about 9 MW_e . A parallel program of well workovers and new drilling was initiated, preceded with surface exploration studies and revision of existing production history and reservoir conceptual model. A substantial gain in power production in year 2000 resulted from cleaning calcite plugs out of existing wells in the center wellfield and by properly cementing casing of well MT-31. Drilling of new and deep wells OM-51 to OM-54 in 2001–2002 only added about 8 MW_e to the total generation. Modern drilling technologies like aerated fluids and directional drilling were applied and mud use excluded in open hole sections. Substandard drilling practices were therefore not to be blamed for the only 2 MW_e success per well.

At this point in time Ormat made a strategic decision in its field development, by installing the 7 MW_e binary unit. It is mostly operated with fluids from the shallow reservoir. Calcite scaling problems continued to persist in many of the shallower wells, requiring inhibitor system in 7 out of 11 production wells. Acidizing units were employed in and after 2003. These acid jobs allowed for continued operation of wells that had tendency to flash and scale into formation. Additionally Ormat was able to stimulate feedzones previously clogged by drilling mud. In particular at the Eastern wellfield where 100 % brine injection now takes place, thereby stopping previous brine dumping into Lake Managua.

Among recent resource studies undertaken, a tracer experiment in 2002 to 2003 may explain rapid loss in enthalpies observed in most production wells after 1991. Napthalene disulfonate tracers were injected into four wells at the Eastern wellfield boundary. Tracer recoveries were monitored in 12 production wells for a period of 8 months (Figure 4). The figure shows that the injected fluid shows up in all production wells but dry steam well MT-43. Therein is the field best producer, well OM-53, which taps deep zone at 1600 m b.s.l. As to be expected chemical breakthrough times are fastest in the shallow and intermediate depth wells while slower in deeper wells. Tracer concentrations are sizeable in all the wells studied. These data suggest that there is a direct connection between the East wellfield and production wells, most likely by fractures. The Eastern wellfield seems to acts as a constant pressure boundary, possibly due to permeable faults that cut to surface. This boundary recharge is unfortunately cold. It is then located close to well RMT-18 due to its reversed temperatures at depth (100-150 °C, see Figure 2).

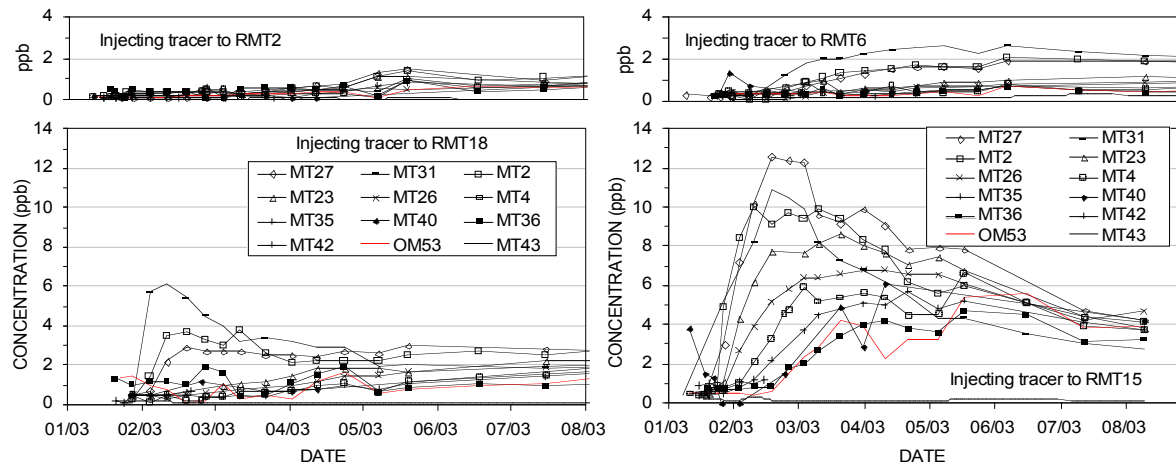


Figure 4. Tracer recoveries in Momotombo wells. Tracers were injected in November 2002 (RMT-15) and January 2003.

4. Volumetric Models

Initial generating capacity estimates for Momotombo are most often based on volumetric models. In these, a thickness and area extent of a possible reservoir are estimated, together with likely temperature range, porosity and other formation properties. Furthermore, one needs to estimate a recovery factor for the total heat reserve, turbine efficiency in converting raw heat

Table 1. Properties of a Momotombo volumetric reservoir model (Table VII-6.1 GeothermEx 2001).

Property	Minimum	Most likely	Maximum
Reservoir area (km ²)	2.3	5.2	7.0
Thickness (m)	2000		3000
Porosity (%)	3		7
Temperature (°C)	250		285
Recovery factor (%)	10		20
Generation capacity (MW _e)	109	137	171
Area based load (MW _e /km ²)	24.1	28.9	34.3

to electricity, load factor and utilization period in years. Geothermex (2001) recently carried out a volumetric model study for Momotombo. Table 1 summarizes some major assumptions made for the resource properties. This model suggests that a possible Momotombo resource can sustain more than 100 MW_e generation load.

Other older models for Momotombo came to a similar conclusion for 30 years generating capacity. That the possible reservoir should sustain on the order of 100 MW_e (DAL, 1994, pages 5-8). When this number is compared with Figure 3 it is obvious that there is a substantial discrepancy between actual and possible generation, a factor of 3 or higher. One reason has to do with area and thickness assumptions made in the volumetric models. Another is the massive cold fluid recharge from East. A comprehensive study of Momotombo initial temperatures shows that reservoir area hotter than 240 °C is within 2 km² in size at 500, 800 and 1300 m b.s.l. (Porrás et al., 2007). Other field data gathered after the model development, like poor well success below 1600 m depth,

indicates that a reservoir thickness of 2-3 km is an overestimate. Reducing the area extent in Table 1 from 5 to 2 km² may half the most likely estimate. If the reservoir thickness is also reduced and cooling from the East boundary accounted for, one can conclude that the current stabilized generation of 32 MW_e is reasonable for the proven reservoir.

5. Numerical Reservoir Models

Two full scale 3-D well-by-well models have been calibrated for Momotombo. The older one was developed by DAL (1994). It is based on a reservoir simulator, GEOSIM, being developed in Italy at that time (O'Sullivan et al., 2001). The model assumes a rectangular mesh, 16.5 x 16.5 km in area and 3 km thick. Total number of elements was 640. At this time 39 wells had been drilled in Momotombo. The deepest one reached 2050 m depth. Field data that constrained the DAL model were initial temperatures and pressures, production histories and pressure drawdown. The reservoir was able to sustain around 45 MW_e generation and flashing was widespread in the shallow reservoir. Reservoir cooling was therefore still to be seen.

The DAL model predicted 15 year save production rates of 50 to 90 MW_e. The lowest estimate assumed no make-up drilling while the 90 MW_e required drilling of 4 additional deep wells accompanied with revised injection strategy. In addition, the modelers elaborated on a possible deep resource at 1600 to 2600 m depth. If this layer could be confirmed, the predicted generating capacity rose to 150 MW_e.

Figure 5 shows a cross section of permeability distribution in the DAL model. Of particular attention should be the above-mentioned hypothetical reservoir layer at 1600 to 2600 m depth. Unfortunately repeated drilling into this depth interval was later unable to locate commercial permeability. Of wells 40, 41, 42, 43, 51, 52, 53 and 54, drilled this deep after model calibration, only 43 is able to discharge 1.5 MW_e from within the layer. Current drilling success is, therefore, contradicting a mean 5 MW_e deep well output presumption made in the model. Consequently the existence of deep resource has to be questioned, as wells as the 150 MW_e generating capacity estimate. Furthermore, as the DAL study is not accounting for cooling from the East, the 50-90 MW_e prediction should be revised, preferably by a recalibration effort.

Another 3-D reservoir model on Momotombo was calibrated in 2005. A detailed description of this model is given by Porras et al. (2007). Length of production history had more than doubled since DAL calibrated its model in 1994 and 8 new and deep wells had been drilled. Of particular importance in the model development were datasets confirming shallow reservoir cooling. The East field constant pressure boundary was therefore introduced to the model mesh. Inverse methods were applied for improved match to field data (iTOUGH2).

This model came to the conclusion that the Momotombo reservoir should sustain total generation of about 50 MW_e for another 15 years. The additional 20 MW_e generation to the current 32 MW_e was modeled by 4 new wells yielding optimistically 5 MW_e each. Increased production from shallower wells also had to take place. Due to a single porosity modeling approach, it was decided not to simulate observed tracer recoveries (Figure 4). This is a drawback since the tracer data suggests that fluid flow is fracture controlled in the subsurface. The model consequently was unable to simulate accurately observed enthalpy loss in some of the shallower wells. One should therefore be precocious when using this model for long term resource management strategies in Momotombo. The single porosity approach namely generates optimistic enthalpy predictions when it comes to account for cooling by injection and boundary recharge.

6. Discussion

The less than anticipated performance of the Momotombo resource is naturally of concern. It can be argued, however, that the current situation is acceptable, bearing in mind small size of the productive and proven reservoir. As mentioned above, surfaces hotter than 240 °C were on the order of 2 km² in the uppermost 1.5 km of the reservoir. If normalized with the stable 32 MW_e generated at present, mean output is in excess of 15 MW_e/km². Similar area based generating capacity is derived if size of the wellfield is used as a reference. The 15 MW_e/km² load is comparable in success to many other reservoirs of larger area and higher temperature worldwide (Sarmiento and Bjornsson, 2007). As an example the ongoing >400 MW_e Hengill project in Iceland is assuming 10-15 MW_e/km² in new wellfields hotter than 240 °C.

Evaluation of results of deep drilling in Momotombo is, on the other hand, of grave concern. The 4 wells drilled by Ormat, for example, only yielded like 2 MW_e/well. Earlier drilling of wells 40-43 proved of similar success, just below 2 MW_e/well. Furthermore, these older wells currently yield less than 1 MW_e/well some 10 years after drilling. For comparison, the current mean well output is only 0.75 MW_e (Figure 3). As the field operation has been struggling to touch a 2 MW_e per well barrier, the last eight wells drilled can be regarded as a welcomed exception.

The existence of a cold and constant pressure boundary at the Eastern wellfield margin puts a limitation on maximum generating capacity of the Momotombo resource. Unlike in most other reservoirs, the heat reserve is namely limiting generation, not the mass reserve. Aggressive production in the center and deep wellfield will stimulate cold fluid recharge from the East, to be heated with a constant size and diminishing heat reserve between injection and production points. This is shown schematically in Figure 6. Current fluid production from the shallow and the deep reservoir is already supported by recharge from that cold boundary (Figure 4). Its alien chemical composition may explain calcite scaling plugs that begin to form downhole after 1996. The tracer data suggests that the boundary recharge fluid is channeled by a fracture network of a limited surface area and, thereby, limited conductive heat flow between rock matrix and the fractures. The greater the production, the less can the mass recharge from East warm up before entering production points. This will in turn negatively impact total steam flow from production wells, as declining enthalpies will both reduce total discharge and steam fraction of the produced fluid.

One way of increasing the generating potential of Momotombo may lie in managing the boundary recharge from East. This will be complex technological and hydrological challenge. Injecting some brine to the East of the constant pressure boundary and deeper looks most obvious. Ormat is already working on this option after successful stimulation of well MT-1 recently. Another and more expensive option for added generation is to drill deep wells, inside and outside the current exploitation concession, in order to increase distance between the constant pressure boundary and production points. Cost should be expected high as the average success of deep wells in Momotombo is currently below 2 MW_e per well. These new wells may unfortunately also reduce deep recharge to the shallow reservoir and, thereby, cut steam generation from some of the existing

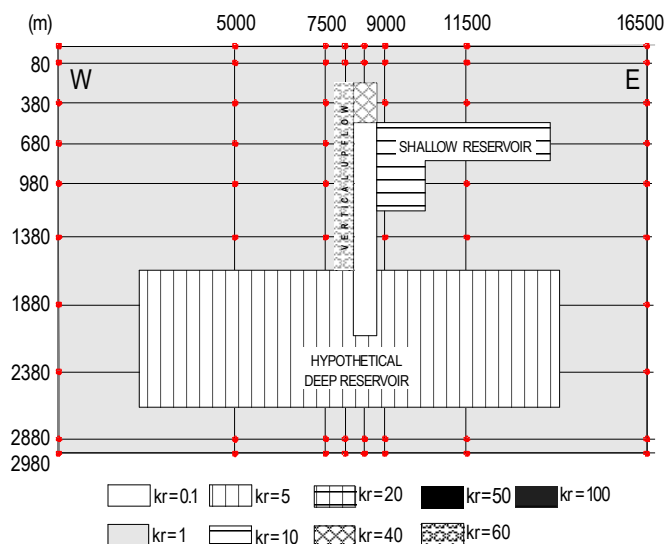


Figure 5. A resistivity cross section through DAL (1994) reservoir model.

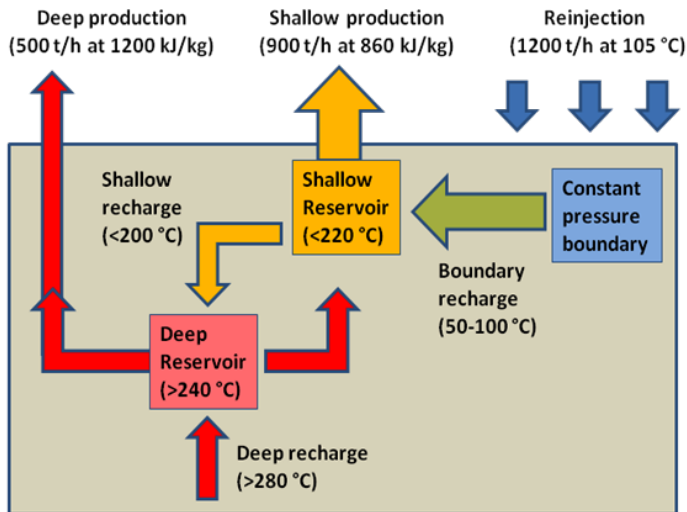


Figure 6. A schematic of current flow paths in Momotombo.

wells. Decision hereon therefore needs careful financial and operational planning.

Finally it should be mentioned that the current generation strategy in Momotombo is aggressive and may not necessarily qualify as renewable, due to observed cooling trends in the shallow reservoir. Bearing in mind that Nicaragua desperately needs to boost its own energy production, the Momotombo geothermal operation may nevertheless qualify as sustainable development. The technical and geoscientific work currently carried out in Momotombo namely has the potential to strengthen geothermal operations in Nicaragua and elsewhere. This paper and many earlier ones on Momotombo can hopefully assist in this endeavor.

7. Conclusions

Main observations and conclusions drawn in this paper can be summarized as follows:

Best production zones in the Momotombo geothermal reservoir are confined to about 2 km² area, initially hotter than 240 °C, at 500 to 1300 m depth. Repeated attempts to find permeability below 1600 m have been disappointing and succeeded only in 1 well out of 17.

The Eastern wellfield, where current reinjection takes place, behaves like a constant pressure boundary of only 100-150 °C temperature. Fracture dominated, high permeability formation connects this boundary to production points.

With extended production from hot wells, cold recharge has led to substantial enthalpy decline and increased calcite scaling potential of many wells and feedzones. Negative impact on the resource behavior has been partially mitigated by mechanical cleaning operations, acid jobs, commissioning of a 7 MW_e binary unit, deeper drilling, revised injection strategy, and by installing scaling inhibition systems. Brine pollution of Lake Managua conveniently also has been stopped with improved reinjection capacity.

Older generating capacity estimates of 100-170 MW_e rely on volumetric models, which assume considerably larger production reservoir than seen in current field data. If the proven 2 km² reservoir at 500-1300 m is used as a base scenario for volumetric model, these generating capacity estimates should be reduced by a factor of 2-3. Observed cooling from the East boundary may also further lower these estimates.

When a numerical reservoir model of DAL was developed in 1994, adverse effect of cold recharge was yet to be seen in the field data. The model therefore wrongly predicted another 15 years of 50 MW_e operation without make-up drilling. The DAL model also suggested that 150 MW_e could be tapped from hypothetical layer at 1600 to 2600 m. Well success below 1600 m depth contradicts this hypothesis and will, as a best case scenario, result in high drilling cost.

A numerical model, developed in 2005, was calibrated against much larger dataset and accounted for the constant pressure boundary to the East. The model suggests that current field generation can be increased to as much as 50 MW_e by additional deep drilling. Its single porosity approach makes the model, unfortunately, optimistic when it comes to predict cooling. Cost of additional drilling needs therefore to be recovered faster than elsewhere.

The proven 2 km² and 1100 m thick Momotombo resource yields a stabilized area based generating capacity of 15 MW_e/km², compared to 10-20 MW_e/km² world average for reservoir hotter than 240 °C. The current operation of the proven reservoir is consequently deemed successful and professional.

Maximum generating capacity of the *proven* Momotombo reservoir seems more controlled by heat instead of mass reserves, unlike in most other geothermal reservoirs. A large *possible* heat reserve still resides deeper down, within and also outside the current exploitation concession boundaries. Unfortunately it appears expensive to develop. Mean deep well success may be in the order of 2 MW/well with a decline of 5 % per year.

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