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CONCEPTUAL MODEL AND RESOURCE ASSESSMENT FOR THE OLKARIA GEOTHERMAL SYSTEM, KENYA

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ABSTRACT

The first published conceptual model of the Olkaria geothermal system is 37 years old at present. It has been upgraded intermittently through time, as more information on the geothermal system has become available. The conceptual model was revised yet again during 2011 – 2012 on the basis of all available geological and geophysical information, temperature and pressure data, various reservoir testing and monitoring data as well as information on the chemical content of reservoir fluids. Most important are data from about 60 deep wells drilled in the area since 2007. The Olkaria geothermal resource can be split in two; a heavily explored part where extensive drilling has delineated the resource and long-term utilization experience exists, and a less explored part where drilling has been limited and mainly indirect indications of an exploitable resource exist. The conceptual model for the former part is quite accurately defined while the model for the latter part is very speculative. At least three deep magmatic heat sources are assumed below the heavily explored part of the system with hot water up-flows into the four main well-fields. The resources anticipated in the less explored part require exploration through comprehensive surveying and drilling. The electrical generation capacity of the heavily explored part of KenGen's concession area in Olkaria is estimated to be about 630 MW_e based on a volumetric resource assessment, lumped parameter pressure response modelling and detailed numerical modelling. This includes 150 MW_e already installed and 280 MW_e under construction. The results of the three different assessment methods are quite comparable, which adds confidence to the results. The electrical generation capacity of the less explored part is estimated to be about 300 MW_e based on a volumetric assessment, an estimate that needs to be confirmed through comprehensive exploration and drilling.

1. INTRODUCTION

The Olkaria geothermal resource is located in the Kenya Rift valley, about 120 km from Nairobi. Geothermal activity is widespread in the Kenyan rift and 14 major geothermal prospects have been identified (Figure 1). The Olkaria geothermal field is inside a major volcanic complex that has been cut by N-S trending normal rifting faults. It is characterized by numerous volcanic rhyolitic domes, some of which form a ring structure, which has been interpreted as indicating the presence of a buried volcanic caldera (Figure 2). Olkaria is surrounded by further geothermal prospects as shown in Figure 1.

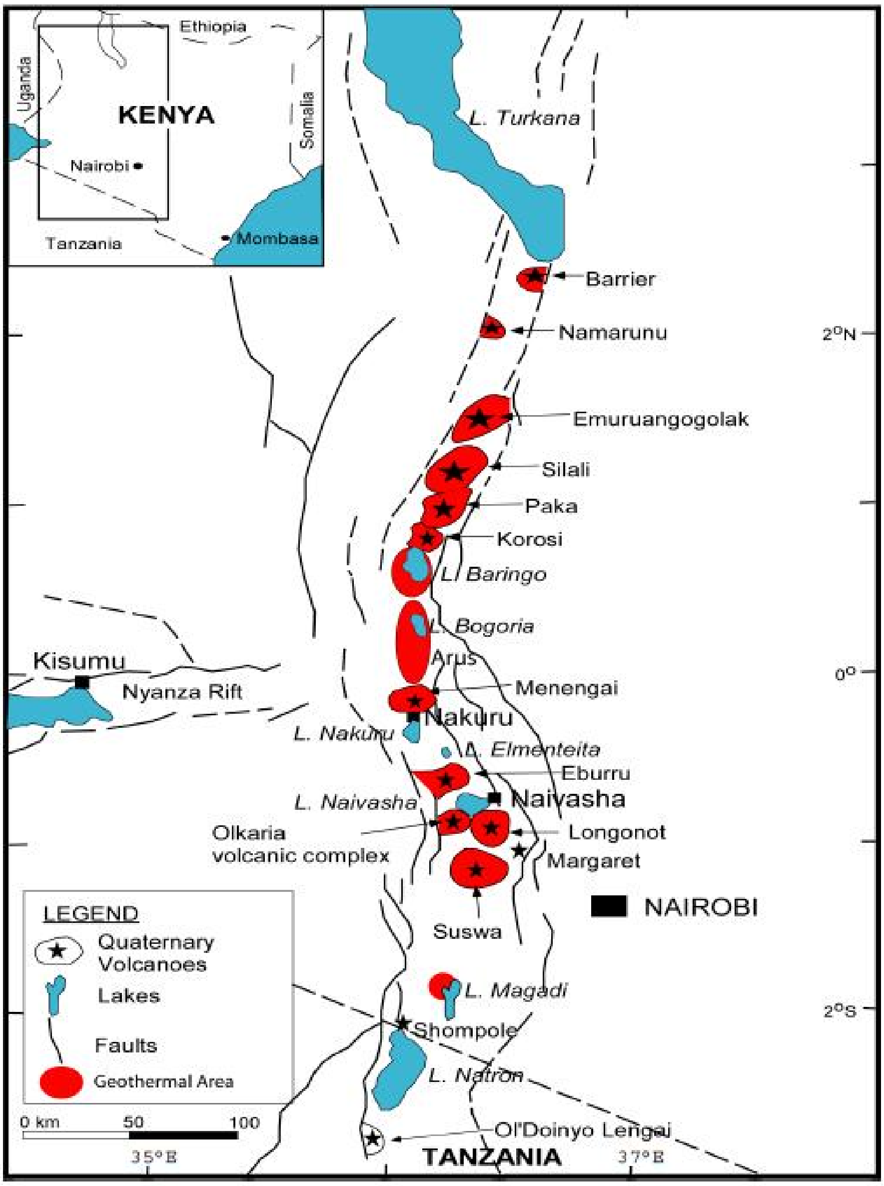

FIGURE 1: Map showing the location of the Greater Olkaria Geothermal Area within the Great Rift Valley of Kenya. Also shown are other volcanic and geothermal centres (Ofwona, 2010)

Exploration of the Olkaria geothermal resource started in 1956 with deep drilling commencing in 1973. A feasibility study in 1976 indicated that development of the geothermal resource was feasible and consequently a 30 MW_e power plant was constructed (Ouma, 2010). Three power plants are currently installed in the field and producing electricity; Olkaria I with 45 MW_e capacity, Olkaria II with 105 MW_e capacity and Olkaria III with 48 MW_e capacity. The first two are operated by KenGen while the third is operated by OrPower4 Inc. The Olkaria I power plant consists of 3 units commissioned between

1981 and 1985 while Olkaria II, which also has 3 units, was commissioned between 2003 and 2010. The Olkaria III power plant was commissioned in two phases between 2000 and 2009. In addition the geothermal resources of the NW part of the Olkaria area are utilized both for direct heat and small scale electricity generation by the Oserian flower farm. Finally KenGen has recently started operating a well-head unit of 5 MW_e capacity. The parts of the Olkaria geothermal field being utilized or under development have been subdivided into sectors that include Olkaria East (Olkaria I), Olkaria Northeast (Olkaria II), Olkaria West (Olkaria III) and Olkaria Domes (Olkaria IV).

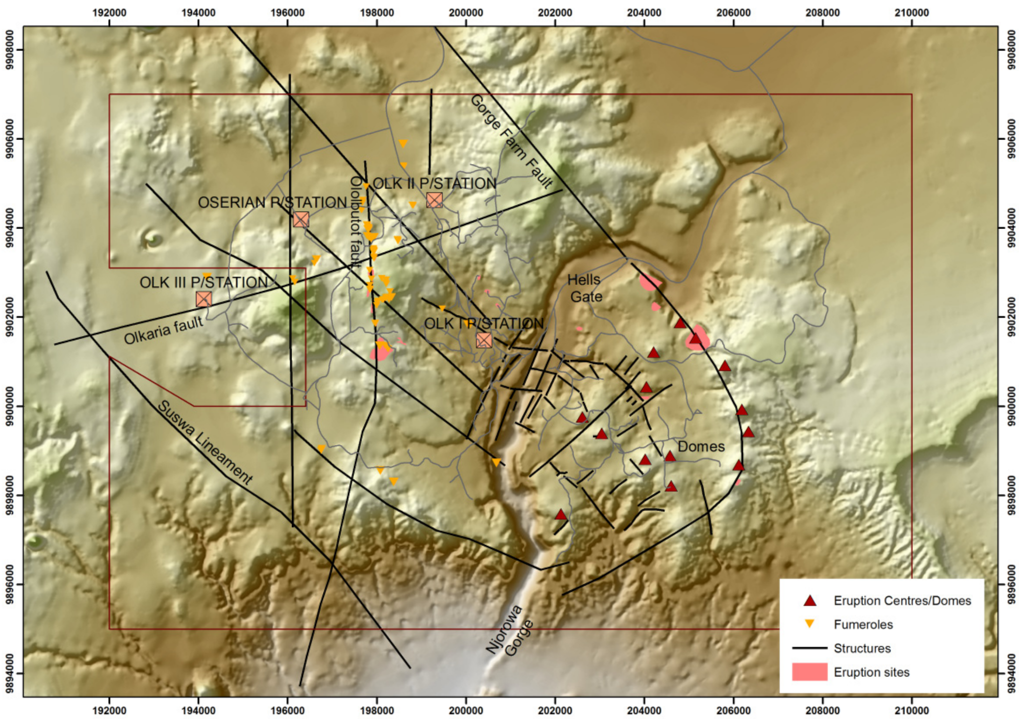

FIGURE 2: Map showing KenGen's geothermal concession area in the Olkaria volcanic complex, extending up to Lake Naivasha. The map also shows some of the main geological features of the area and the power plants in operation

KenGen's present estimate of the possible generating capacity of their 204 km^2 total concession area in Olkaria indicates that it may sustain as much as an additional 840 MW_e long-term generation (KenGen in-house data). Of these 280 MW_e have entered the implementation phase, a 140 MW_e expansion of Olkaria I and a 140 MW_e installation in Olkaria IV. As a result of intensive production drilling (60 wells) in progress since 2007 steam availability corresponding to as much as 440 MW_e (based on discharge testing of each well following heating-up) has been inferred in the Olkaria East and Olkaria Domes sectors (KenGen in-house data). Therefore a capacity of about 400 MW_e or moer still remains untapped, according to KenGen's estimates. Figure 3 shows the geothermal wells drilled to-date by KenGen.

The apparently large untapped resource was the motivation to carry out an optimization study for the Greater Olkaria Geothermal System in 2011 - 2012. The objectives of the study were to assess the energy production potential of geothermal resources within KenGen's 204 km^2 concession area in Olkaria, mainly through comprehensive reservoir modelling, assess the feasibility of continued and increased production, as well as to propose an optimized development plan for the area. This work was awarded to a consortium from Iceland composed of Mannvit hf, ÍSOR, Vatnaskil ehf and Verkís hf. The results of the optimization study have been presented in several in-house KenGen reports, while this paper summarizes the results of a revision of the conceptual model of the geothermal system and the results of production capacity estimates arrived at through three types of resource modelling. This paper is to a large extent based on Axelsson et al. (2013).

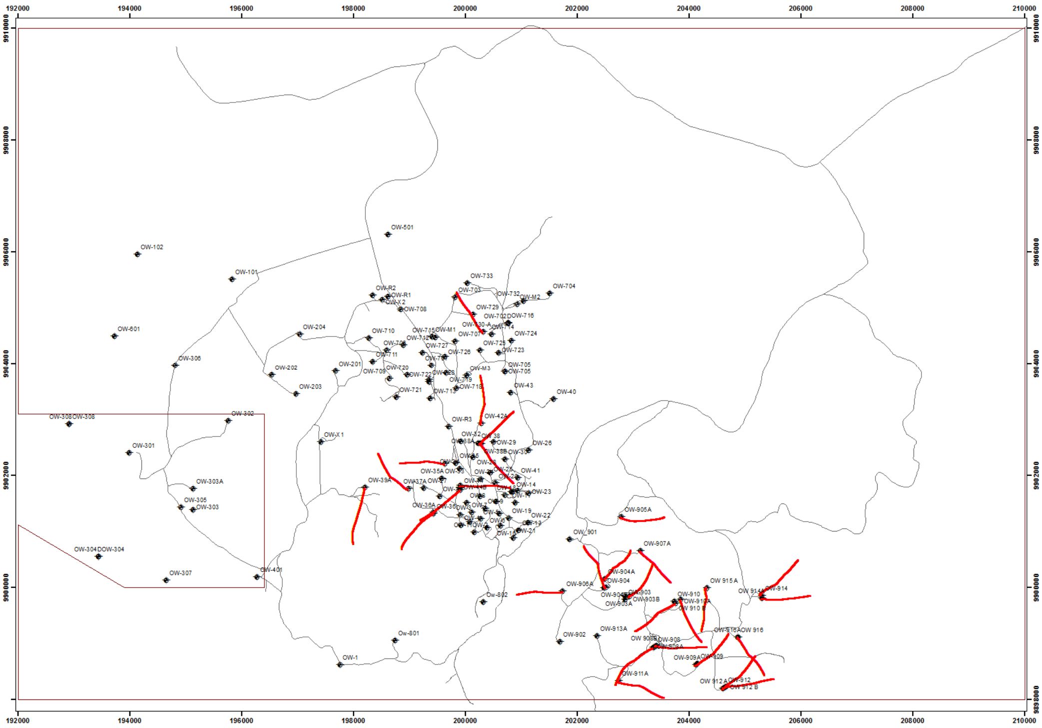

FIGURE 3: Map showing the location of wells in Olkaria drilled by KenGen up to middle 2012, horizontal trajectories of directionally drilled wells shown by red lines. The map covers KenGen's concession area, whilst OrePower4's concession can be seen on the left

The conceptual model of the Olkaria geothermal system has been constantly evolving during the last 4 decades, as reviewed below. The same applies to reservoir assessment and modelling.

2. UPDATED CONCEPTUAL MODEL

2.1 General

Reliable conceptual models of geothermal systems are the key to successful development of all geothermal resources and emphasis is increasingly being put on the development of such models, especially during geothermal exploration and development, as well as their revision during long-term utilization and resource management. Conceptual model revision is obviously vital during expansion of geothermal operations, as is on-going in Olkaria. Conceptual models are descriptive or qualitative models incorporating, and unifying, the essential physical features of the systems in question (Grant *et al.*, 1982).

Conceptual models are mainly based on analysis of geological and geophysical information, temperature and pressure data as well as information on the chemical content of reservoir fluids. Monitoring data reflecting reservoir changes during long-term exploitation, furthermore, aid in revising conceptual models once they become available. Conceptual models should explain the heat source for the reservoir in question and the location of recharge zones as well as the location of the main flow channels and the general flow patterns within the reservoir. A comprehensive conceptual model should, furthermore, provide an estimate of the size of the reservoir involved. Conceptual models are ultimately the foundation for all geothermal resource assessments, particularly volumetric assessments and geothermal reservoir modelling. In addition, conceptual models are an important basis of field development plans, i.e. in selecting locations and targets of wells to be drilled.

The conceptual model of the Olkaria geothermal system has, of course, evolved through time (more than 35 years) as more information has been accumulated through surface exploration, drilling, utilization and reservoir engineering work. The first published version of the conceptual model was presented by SWECO and Virkir (1976). It was very simple due to the limited drilling done at the time (see Figure 4). Later revisions saw the model expanding to cover more of the Olkaria area and include several zones of hot up-flow, first in the Northeast and West sectors and later in the East sector as well (see Ofwona, 2002). Ofwona (2002) presented an updated version of the conceptual model. According to his revised model the hydrothermal systems of western and eastern Olkaria are clearly separated by the low temperature zone of central Olkaria. He postulates two possible up-flow zones in Olkaria Northeast and one up-flow zone in Olkaria East, with a down-flow separating Olkaria Northeast and Olkaria East. Extensive boiling also occurs in the up-flow zones to form steam caps below the cap rock, according to this revision. Cold water recharge into the Olkaria geothermal system is assumed to occur from all directions in that model (see Figure 5).

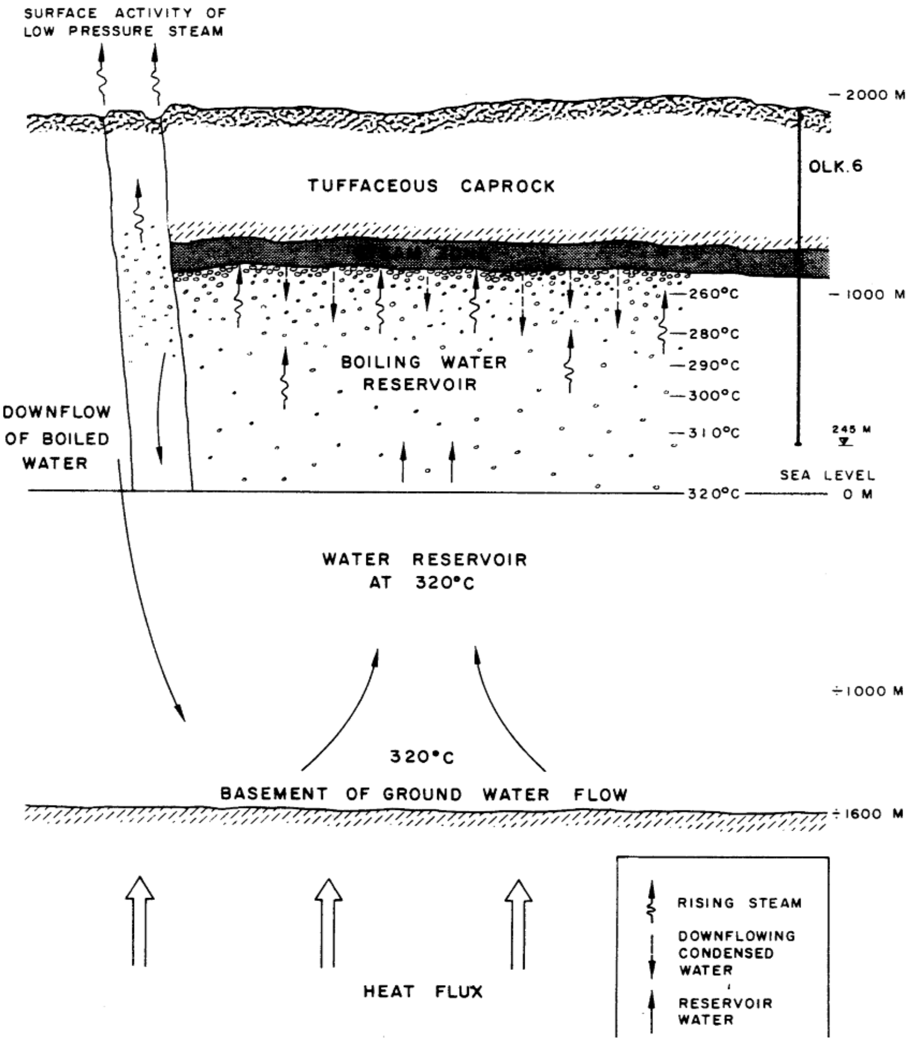

FIGURE 4: A pictorial rendition of an early conceptual model of the Olkaria East geothermal system (SWECO and Virkir, 1976)

The latest version of the Olkaria conceptual model, prior to the one presented here, is the one developed by West Japan Engineering Consultants Inc. and subcontractors from 2005 to 2009 (KenGen in-house report). This model is quite comprehensive and appears to be still mostly valid. Extensive new data have become available during the last 2–3 years, however, mostly through the intensive drilling program KenGen is conducting, prompting the update discussed in this paper.

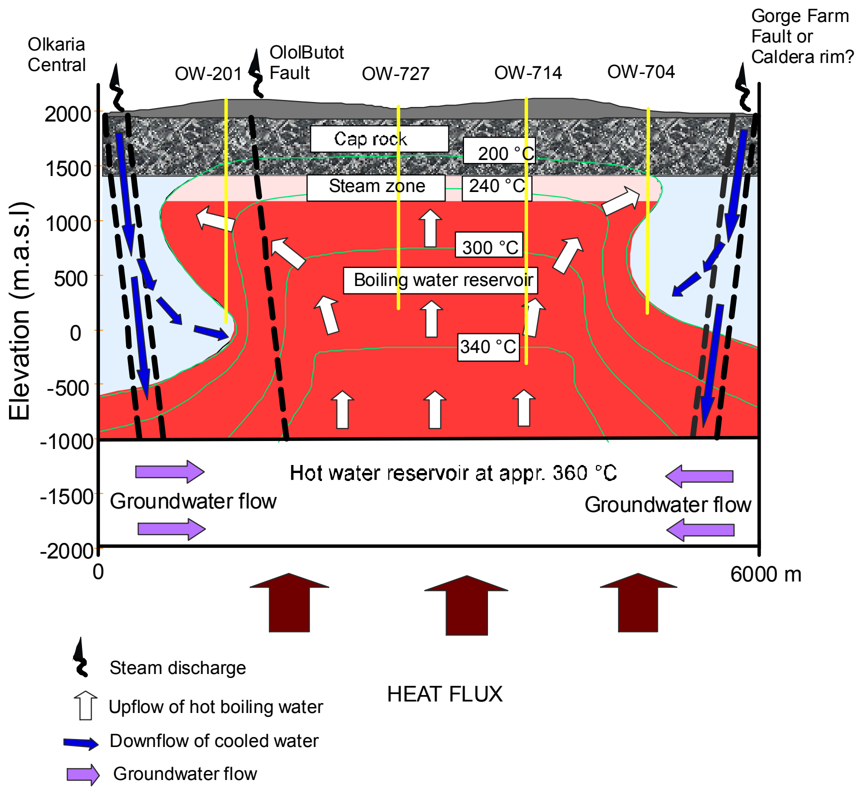

FIGURE 5: A revised conceptual model of the Olkaria East geothermal system from 2002 (Ofwona, 2002)

2.2 Geological data

The relevant geological data for the Greater Olkaria Geothermal System includes both information on surface geology and borehole geological data, which have been viewed by three-dimensional visualization software. These include both lithological and alteration analyses of drill cuttings from boreholes that have been drilled in the field.

The most important input from geological studies involves defining and understanding the permeability structure of a geothermal system. Permeability in the Olkaria system is fracture-dominated, which is e.g. evident from the high well-to-well variability in the depth to high-temperature alteration. Flow paths are controlled by predominantly N-S, NW-SE and NE-SW trending faults (see Figure 2). In addition to the main faults of the system the ring structures encircling the Domes field represent a possible inner and outer rim of the proposed Olkaria caldera. Both the inner and the outer ring structures connect to the Gorge Farm fault, located north and east of the main production area and possibly extending north to Lake Naivasha. Cold water is believed to flow into the Olkaria system through the N-S fault system along the Ololbutot fault, which also is associated with plentiful geothermal surface manifestations.

In spite of attempts to incorporate available data into a single model, the results are still rather inconclusive. This infers that the data resolution is insufficient in relation to the complexity of the geothermal system. Therefore, more detailed mapping of the geothermal system through the available boreholes is needed, especially the correlation between permeability and known geological structures. This lack of refined structural control of the geothermal system makes borehole siting more challenging. The method adopted by KenGen has been of a cautious nature where the well-fields have in general been expanded both by short distance step-out wells from areas of good productivity, as well as through drilling into deeper and hotter parts of the system. This approach has turned out to be sensible as can e.g. been seen by the success of the KenGen drilling program in recent years.

2.3 Geophysical data

Subsurface resistivity data (EM data including TEM and MT) and micro-seismic monitoring data are considered the most important geophysical data in the case of Olkaria. Good quality data of the former type are only available for limited parts of the Olkaria area, in particular the Domes sector, while such data are almost entirely lacking in other parts of the area. Further EM data collection is planned by KenGen. Most significantly the available resistivity data support the hypothesis that exploitable geothermal resources extend much further to the east and southeast in the Domes sector than previously assumed, as supported by other types of data (see below).

Micro-seismic data collected in the Olkaria area from 1996 to 1998 have provided highly valuable data for the conceptual model of the Olkaria geothermal system. This includes both location of the seismic events as well as information on S-wave attenuation derived from the data, which has been interpreted as reflecting volumes of partially molten material (Figure 6). The largest of these volumes are found below the Olkaria Domes, Northeast and West production fields, with other smaller attenuating bodies possibly indicating further undiscovered geothermal resources.

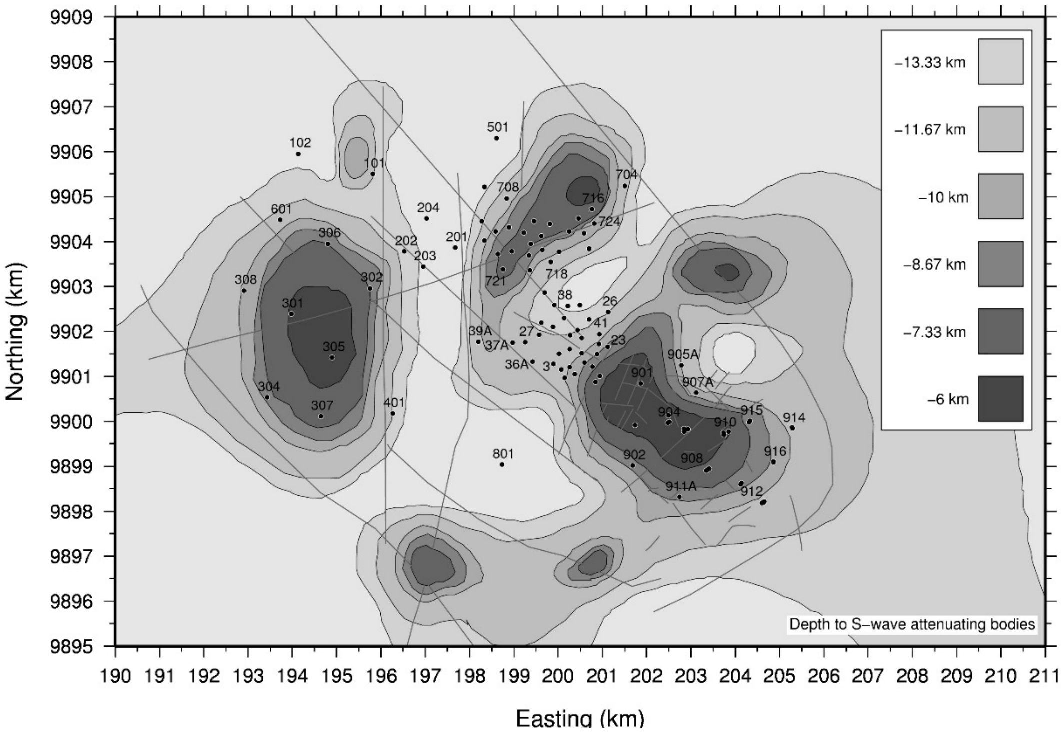

FIGURE 6: Contour map of the depth to the top of attenuating bodies beneath the Olkaria geothermal field along with structural features in the area and location of drilled wells. Based on in-house KenGen reports and Simiyu (2000)

2.4 Reservoir and chemistry data

The temperature and pressure model for the geothermal system, which has been set up during the Optimization Study, is at the core of the conceptual model development and resource assessments discussed here. It also provides an essential basis for the field development for Olkaria. The model is based on so-called formation temperature and initial pressure profiles for all KenGen boreholes in Olkaria. The updated formation temperature and initial pressure model of the Greater Olkaria Geothermal System has provided a significantly clearer picture of the Domes area than has been available up to now. It should be mentioned that some profiles are still uncertain because of insufficient temperature and pressure data for certain wells.

The temperature and pressure model of the Olkaria geothermal system was constantly revised and up-dated during the course of the study presented here, providing an essential basis for the development of the volumetric assessment and numerical reservoir model (see later). Thus new data were constantly incorporated. A glimpse into the revised temperature and pressure model is presented in figures 7 – 11, whilst a more complete view was not possible here.

Other data-sets that aid in revising the conceptual model as well as in establishing the field development plan for Olkaria include the variation in injectivity, estimated transmissivity and well output (mass flow, enthalpy and estimated electrical generation capacity). These have been presented in various project reports (KenGen in-house reports). The great capacity of some wells in the Domes sector is, in particular, noteworthy.

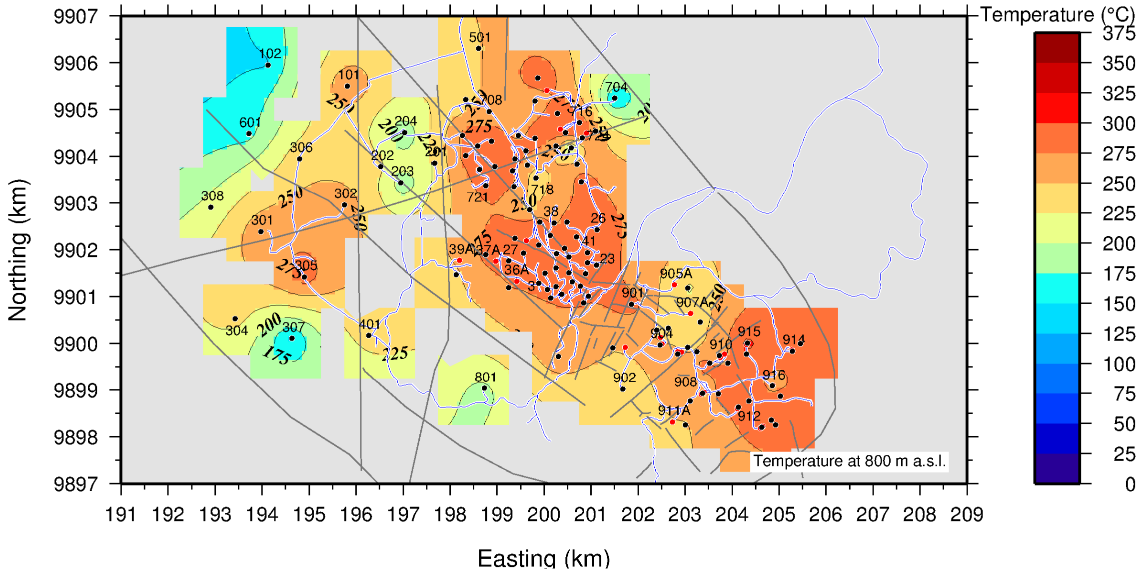

FIGURE 7: Horizontal view of the temperature distribution at 800 m a.s.l. (~1200 m depth) in the revised temperature model of the Greater Olkaria Geothermal System

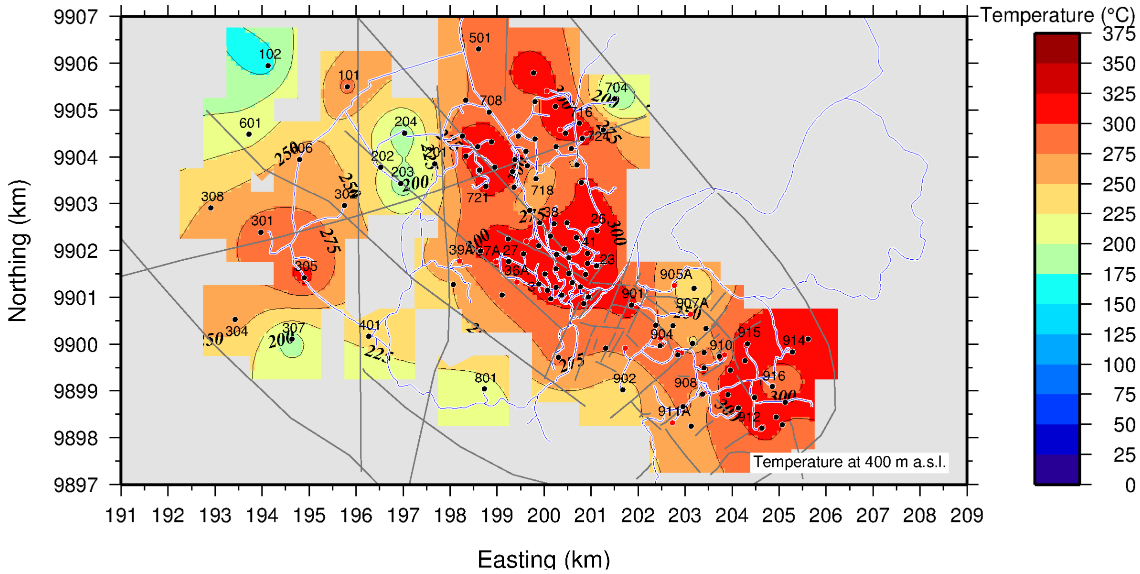

FIGURE 8: Horizontal view of the temperature distribution at 400 m a.s.l. (~1600 m depth) in the revised temperature model of the Greater Olkaria Geothermal System

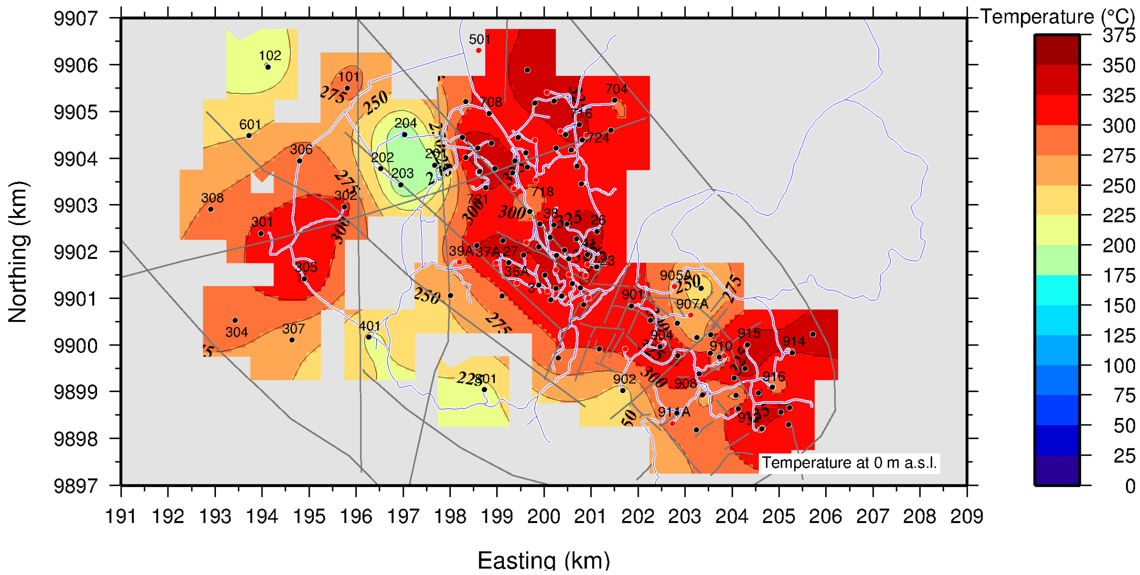

FIGURE 9: Horizontal view of the temperature distribution at 0 m a.s.l. (~2000 m depth) in the revised temperature model of the Greater Olkaria Geothermal System

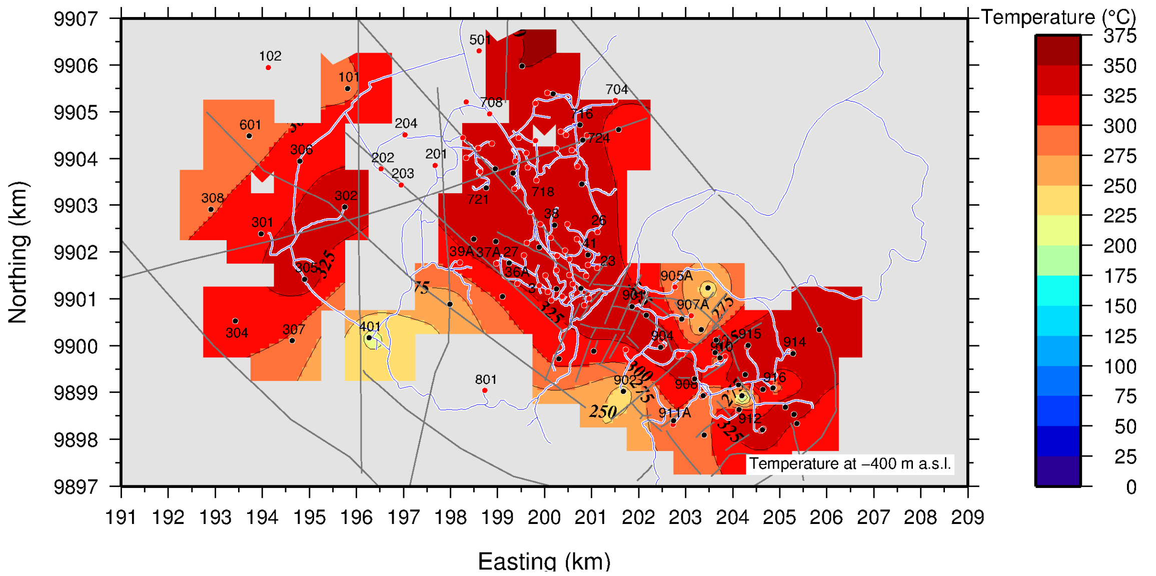

FIGURE 10: Horizontal view of the temperature distribution at -400 m a.s.l. (~2400 m depth) in the revised temperature model of the Greater Olkaria Geothermal System

Additionally to the above information, data on the chemical and gas content of fluid from geothermal surface manifestations and fluid samples from geothermal wells provide important information. The following main results should be emphasized. Firstly, that the chemical content of fluids from the Domes sector support the possibility of an hot up-flow in the southeast part of the Domes as well as supporting the contention that the resources there extend further to the east and southeast (see Figure 12). Secondly, that surface manifestations are widespread in all parts of Olkaria, except the northeast quadrant of the region. Samples from these indicate source temperatures from 240°C to more than 300°C in different parts of the area.

2.5 Revised conceptual model

The revision of the conceptual model for the Greater Olkaria Geothermal System has emphasised (a) interpretation of data not available during development of previous conceptual models, (b) development of a new temperature and pressure model for the system as well as (c) presentation of principal aspects of the conceptual model by a three-dimensional visualization software.

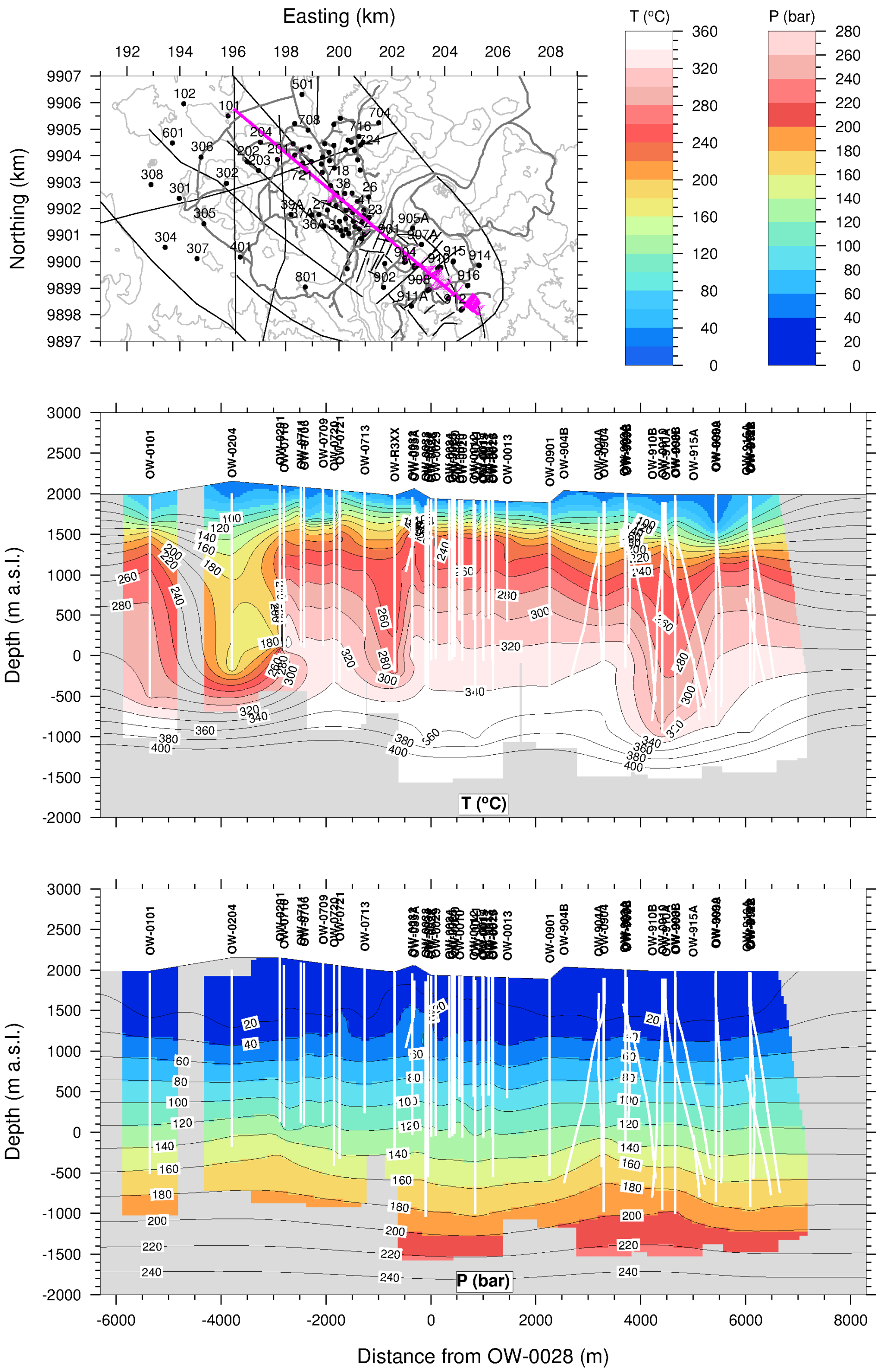

FIGURE 11: A view of the temperature and pressure distribution in a NW-SE cross-section through the Olkaria Geothermal System

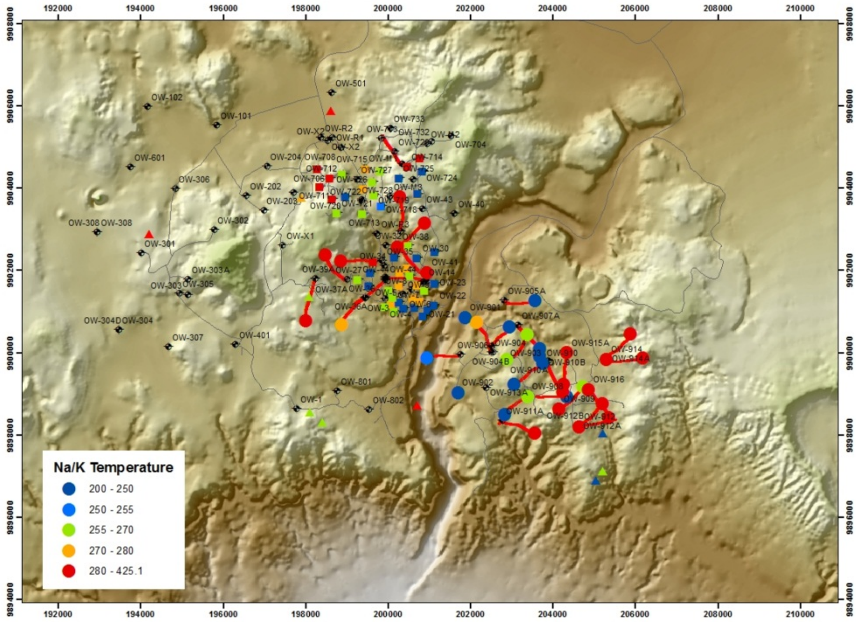

FIGURE 12: Na/K temperatures of Olkaria production wells (based on KenGen in-house chemical data). Larger symbols represent data for recently drilled wells

The main aspects of this most recent revision of the conceptual model are the following:

(1) The Olkaria geothermal resources can be split in two based on the level of knowledge on their nature and characteristics, i.e. the part which has been heavily explored, in particular through extensive deep drilling, and the part that has been drastically less explored. The conceptual model for the former part is understandably much better defined and includes much more detail. The conceptual model for the latter part is less detailed and considerably more speculative.

(2) The heat source of the geothermal system is assumed to be a deep-seated magma chamber or chambers. Three main intrusions are believed to extend up from the magma chamber(s) to shallower depths of 6 – 8 km. These heat source bodies (possibly partially molten) are proposed to lie beneath Olkaria Hill (Olkaria West), in the northeast beneath the Gorge Farm volcanic centre, and in the Domes area.

(3) Four major geothermal up-flow zones are identified from the temperature and pressure model related to these heat sources. Firstly an up-flow zone feeding the West field seems to be associated with the Olkaria Hill heat source body. Secondly two up-flow zones, one feeding the Northeast field and another feeding the East field and the northwest corner of the Domes, are probably both associated with the heat source body beneath the Gorge Farm volcanic centre. Finally an up-flow zone appears to be associated with the ring structures in the southeast corner of the Domes field, related to the heat source proposed beneath the area. The existence of these up-flow zones is supported by Cl^- concentration data and Na/K temperature estimates as well as resistivity data.

(4) Permeability of the Olkaria system is mainly controlled by predominantly NW-SE and NE-SW tending faults as well as the proposed ring structure and intersections of such structures. Colder water flows into the system through the N-S fault system along the Ololbutot fault and possibly into the Domes area from the northeast. The Ololbutot fault presents a flow barrier between the eastern and western halves of Olkaria. Generally, the origin of Olkaria fluids appears to be 50% or more as deep Rift Valley water, with some variability between sectors.

(5) The Olkaria geothermal resource extends further to the southeast in Olkaria Domes than previously assumed. In fact, on-going step-out drilling has not detected the limit, or boundary, of the resource in this region of the Olkaria field. This is supported by temperature and pressure data, well characteristic and output data, fluid chemistry data as well as geophysical data.

(6) Some exploitable resources are expected in the south central and southwest parts of Olkaria, as indicated by limited geophysical data and surface manifestations. The same applies to the northwest part of Olkaria, even though somewhat lower reservoir temperatures may be expected there. Limited resources are anticipated in the far northeast sector of the concession area apart from a limited region to the east and northeast of the East and Northeast production areas, due to limited indications in available resistivity and micro-seismicity data.

3. CAPACITY ESTIMATES

3.1 Overview

The capacity assessments of KenGen's concession in the Greater Olkaria Geothermal Area are based on a division of the area in two, a division which has already been mentioned. In addition a third part/category is introduced here involving the peripheral zone around the heavily explored part. The division is as follows:

(A) The ***heavily explored part*** of KenGen's Olkaria concession area, mainly the Northeast, East and Domes sectors where the existence of an exploitable resource has been confirmed by drilling (Figure 3) and long-term utilization (Olkaria I and II). Linked with the heavily explored part is a third part/category involving the ***peripheral zone*** around the heavily explored part, because of strong indications (lack of well-defined limits) that the present well-fields may be expanded considerably (see Figure 13).

(B) The ***less explored parts*** of KenGen's concession area, where drilling has been much more limited and mostly indirect indications of an exploitable resource exist (further surface exploration also needed). The possible capacity of this part can only be estimated approximately and the realization of its generation capacity will depend entirely on the outcome of the exploration proposed and consequent exploration drilling.

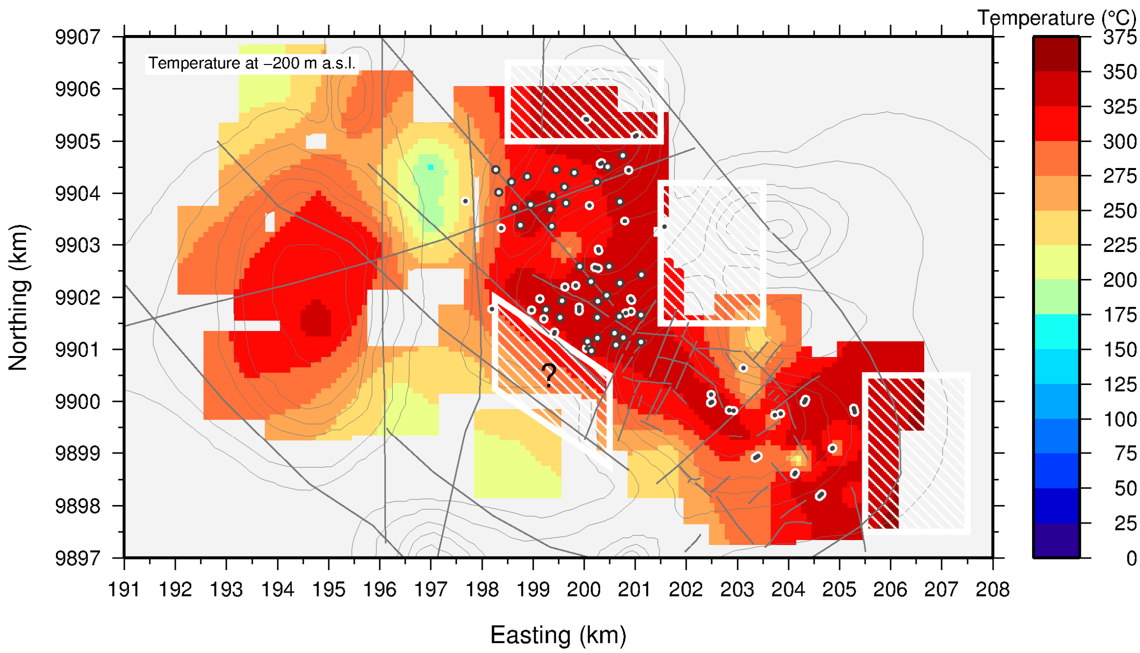

FIGURE 13: Horizontal view of the temperature distribution at 0 m a.s.l. in the temperature model of the Olkaria geothermal system (see Figure 9) along with areas at the edges of the present well-fields, where indications of a boundary haven't been found (white stripes), and expansions of the present well-fields may be possible, termed the **peripheral zone**

The production capacity estimates for the Olkaria geothermal system are based on the results of three types of reservoir assessment and modelling; (i) volumetric capacity assessments for both the heavily explored and less explored parts, (ii) lumped parameter modelling of the pressure response of Olkaria East and Northeast, and (iii) the predictions of the detailed numerical model for the heavily explored part (including the peripheral zone).

3.2 Volumetric assessment

The volumetric method is the main static modelling method used in assessing geothermal resource capacity. The volumetric assessment method is based on estimating the total thermal energy stored in a volume of rock (referred to some base temperature). Subsequently a recovery factor is incorporated, indicating how much of the thermal energy may be technically recovered. The recovery factor is, however, the parameter in the volumetric method, which is most difficult to estimate. The main drawback of the volumetric method is the fact that the dynamic response of a reservoir to production is not considered. This method is often used for first stage assessment, when data are limited, and was more commonly used in the past (Muffler and Cataldi, 1978). It is increasingly being used, however, through application of the Monte Carlo method, which enables the incorporation of overall uncertainty in the results. The volumetric method is e.g. described by Sarmiento et al. (2013) and its application to the Olkaria system by Axelsson et al. (2013).

The main parameters used in the volumetric assessment for Olkaria are presented in Table 1, along with their ranges as used in the Monte Carlo calculations. The resulting probability distributions for the heavily explored part are not presented here (see Axelsson et al., 2013), but they are summarized in Table 2.

TABLE 1: Values and ranges of the principal parameters assumed in the volumetric assessment of the Olkaria geothermal system, employing the Monte Carlo method

Parameter	Heavily explored part	Less explored part
Surface area	40-45 km^2	50-100 km^2
Thickness	2000-2500 m	1000-2500 m
Resource temperature		
% of boiling curve	75-100	-
average	-	200-300°C
Rejection temperature	30°C	30°C
Recovery factor	0.10-0.20	0.05-0.15
Generation efficiency (thermal-electrical)	0.11-0.15	0.08-0.14
Utilization time	50 yrs.	50 yrs.

According to Table 2 the electrical generating capacity of the ***heavily explored part*** of Olkaria may be expected to be above 520 MW_e. The volumetric assessment further indicates that the electrical generating capacity of the ***less explored parts*** of Olkaria may be expected to be above 400 MW_e. These are the southeast extension of the Domes area, where available data indicate that the resource extends still

TABLE 2: Summarized results of a volumetric resource assessment for the Greater Olkaria Geothermal System in MW_e. Numbers refer to estimated generation capacity for 50 years

Monte Carlo results	Heavily explored part	Less explored part
90% confidence interval	450 – 910	320 – 1000
Mean value	670	630
90% limit from cumulative distribution	**520**	**400**

further than drilled so far, as well as the central south and southwest parts of Olkaria, the northwest part of the overall system and a region to the east and northeast of the East and Northeast production sectors. This needs to be confirmed, however, through comprehensive surface exploration and exploration drilling.

Setting these results in the context of a geothermal reporting code (i.e. Australian Geothermal Code Committee, 2008) the generating capacity of the heavily explored part of Olkaria can be classified as a *proven reserve* while the generating capacity of the less explored part should be classified as an *inferred resource.*

3.3 Lumped parameter modelling

Axelsson (1989) presents an efficient method of lumped parameter modelling of pressure response data from geothermal systems and Axelsson *et al.* (2005) present examples of long pressure response histories of several geothermal systems distributed throughout the world, examples which demonstrate its accuracy and reliability. Lumped parameter modelling is also presented at the current workshop by Axelsson (2013).

The fundamental data required for lumped parameter modelling, as outlined above, are production (mass extraction) data and information on reservoir pressure changes resulting from the production. Figures 14 and 15 present the most recent compilation (from early 2012) of such data, for the Olkaria East and Northeast production sectors, respectively.

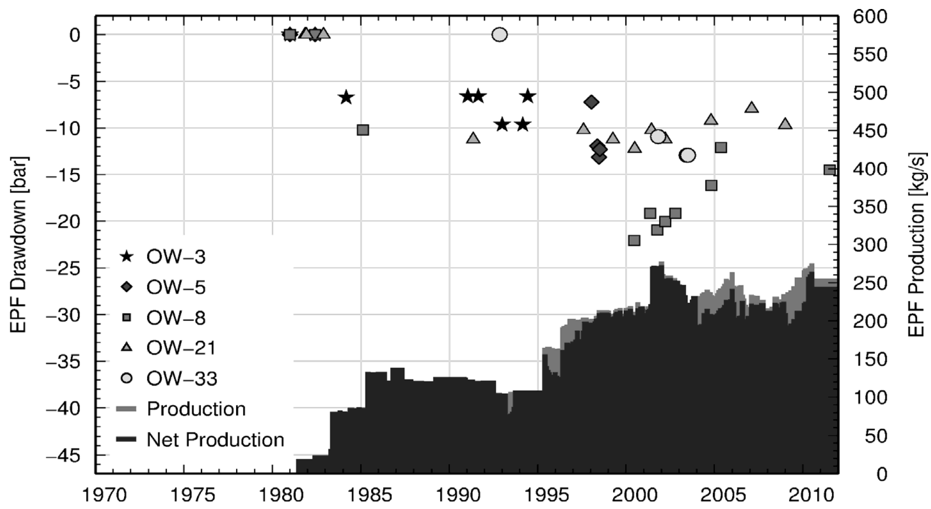

FIGURE 14: Production and pressure response history of the Olkaria East production sector. The pressure draw-down is based on pressure measured at ~650 m a.s.l. and estimated initial pressure conditions for each well (KenGen in-house data)

Figures 16 and 17 show the simulated pressure changes in the two active Olkaria production sectors along with 50-year predictions for two future prediction scenarios. The two scenarios assume that the combined electrical generation of the Olkaria Northeast, Olkaria East and Olkaria Domes sectors corresponded to 520 MW_e (in agreement with the lower bound of the results in Table 2) divided evenly between the three sectors (~170 MW_e each). Based on the average steam-water ratio of Northeast and East production wells (~60% steam by mass) an average mass extraction of 540 kg/s will be needed to sustain this generation, in each of the sectors. The two scenarios were consequently set up as follows:

I) Average production 540 kg/s with 200 kg/s average brine reinjection, for each sector. Net mass extraction is thus 340 kg/s.
II) Average production 540 kg/s, for each sector, with no reinjection.

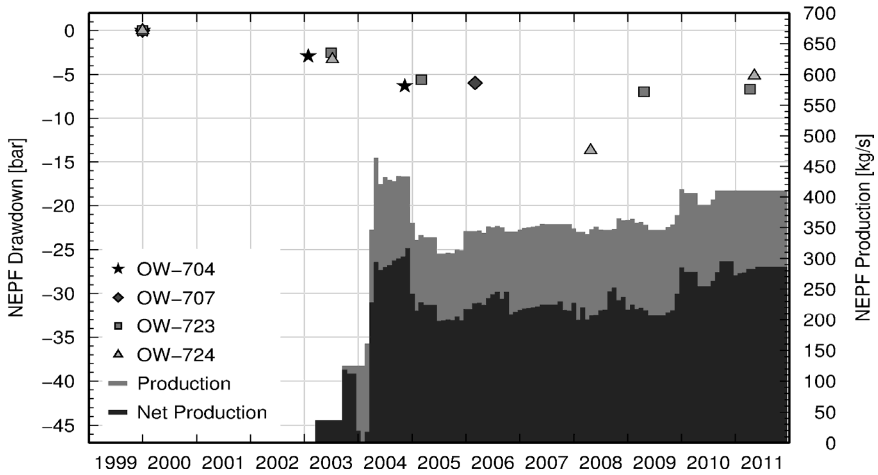

FIGURE 15: Production and pressure response history of the Olkaria Northeast production sector. The pressure draw-down is based on pressure measured at ~1100 m a.s.l. and estimated initial pressure conditions for each well (KenGen in-house data)

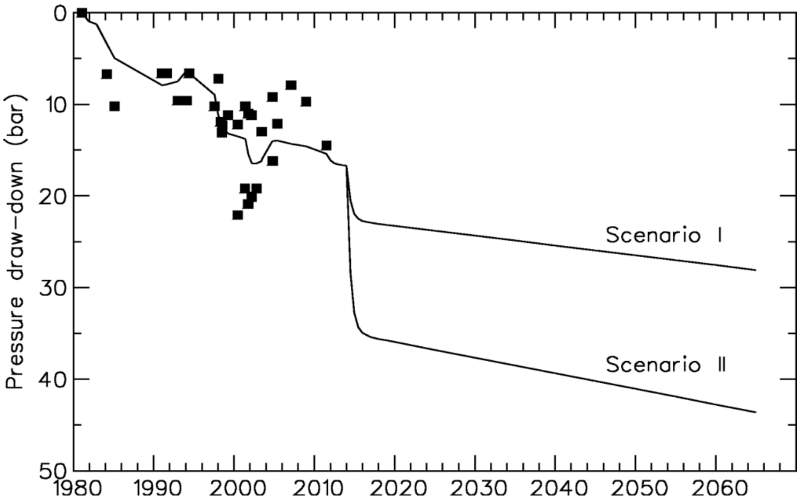

FIGURE 16: Reservoir pressure predictions for the Olkaria East sector calculated by a lumped parameter model for two future production scenarios (see text). Filled squares represent observed data

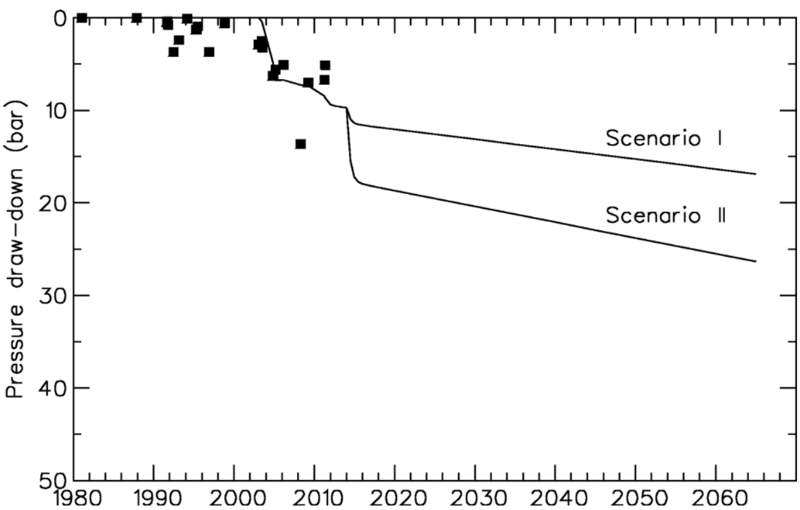

FIGURE 17: Reservoir pressure predictions for the Olkaria Northeast sector calculated by a lumped parameter model for two future production scenarios (see text). Filled squares represent observed data

The main results of the lumped parameter modelling for the Olkaria geothermal system are:

(1) The properties of the lumped parameter models indicate that the whole hydrological system, encompassing the Olkaria geothermal system, is quite large, providing recharge to the geothermal system. The average permeability-thickness of the geothermal system is estimated to be about 10 and 19 Darcy-m, for the East and Northeast sectors respectively, according to the models, which can be considered as close to normal compared with values for other productive geothermal systems.
(2) The predictions for the two scenarios show that the pressure decline for the scenario with reinjection should be manageable. The pressure decline predicted for the scenario without reinjection is quite large, however, especially for the East sector, indicating that such a scenario is not realistic. The short pressure decline history of the Northeast sector indicates that long-term pressure decline there should be somewhat less than the decline in the East sector, at comparable net production.
(3) The principal result of the lumped parameter modelling is, therefore, that brine reinjection, and available steam condensate injection, will be essential if KenGen's future plans of greatly increased electrical generation are to materialize (see later). Otherwise reservoir pressure decline may be expected to be too great. Reinjection will also help minimize pressure interference between production sectors.
(4) It should be noted that the available pressure response data are quite scattered, which adds uncertainty to the pressure response modelling. The length of the Olkaria production history (31 years), on the other hand, enhances the reliability of the model predictions.

3.4 Detailed numerical model

Several numerical modelling studies were carried out for Olkaria from 1980 to 1993. In fact the earliest of these can be considered among the pioneering numerical modelling studies of the geothermal industry. These studies were predominantly carried out by scientists at Lawrence Berkeley National Laboratory in California, chiefly the late Gudmundur Bödvarsson. The first model was a very simple small, two-dimensional, vertical model. The models rapidly became more complex with advancing knowledge on the geothermal system, advances in numerical modelling techniques and rapidly improving computer capabilities.

These modelling studies are described in various internal KenGen reports as well as international publications (Bödvarsson *et al.*, 1987a, 1987b and 1990). Ofwona (2002) also reviews the first two decades of modelling. The first detailed three-dimensional, well-by-well numerical model was set up in 1984, calibrated on basis of the production history of the field up to that time. The final modelling phase lead by Bödvarsson lasted from 1987 to 1993. In this phase the entire Olkaria geothermal system, as known at the time, was modelled. In 1993 the model was revised and calibrated further and used to assess the generating capacity of Olkaria Northeast (Bödvarsson, 1993).

Later Ofwona (2002) updated the 1987 – 1993 model on basis of both new well data and an additional decade of monitoring data. This work was expanded further in 2008. Finally, West Japan Engineering Consultants Inc. and subcontractors set up, from 2005 to 2009, the most detailed numerical model developed up to that time for Olkaria. It was based on their revised conceptual model, covering about half of the KenGen concession area (KenGen in-house reports).

A detailed numerical reservoir model of the Greater Olkaria Geothermal System was set up as part of the project presented here, being by far the largest and most comprehensive model of the system developed so far. It covers the whole KenGen concession area, and beyond. It uses the TOUGH2/iTOUGH2 software for calculating the model conditions and output. The model grid covers 720 km^2 with a total thickness of 3600 m. It is composed of 15 layers and nearly 37,000 elements. The model is calibrated to fit an extremely large dataset of formation temperature and initial pressure for the great number of wells drilled so far. In addition the model fits measured enthalpy of well fluids and pressure drawdown in wells throughout the production period. The model, and its calibration, are described in full detail in KenGen in-house reports.

The model has been used to forecast the response of the geothermal system to six production scenarios, ranging from continuing current production up to an expansion to about 580 MW_e for 30 years. This ultimate scenario assumes 190 MW_e capacity in the East and Northeast production fields, in addition to the 45 MW_e in operation in Olkaria I and 105 MW_e in operation in Olkaria II, as well as 240 MW_e capacity in Olkaria Domes. The results indicate that the system can sustain this, although for the full 580 MW_e scenario the drawdown in the production layers, especially in the Domes field, becomes large over an extensive area. It is however, clear that at present the exploration efforts have not yet delineated the limits of the geothermal system in several areas, most notably to the southeast of the Domes field and north of the Northeast production field. It should also be noted that the results of the numerical modelling for the Domes are not as well constrained as for the two production fields with production histories, even though a great number of wells has already been drilled there.

3.5 Summarized results

Table 3 summarizes the generation capacity estimates for the Greater Olkaria Geothermal System that have emerged as part of the study presented here. These are the results of the volumetric capacity assessment and lumped parameter modelling performed as part of the study as well as the predictions of the detailed numerical model, all of which are discussed above.

The following are the main premises of the numbers presented in the table:

- The range presented as the outcome of the volumetric assessment is based on the 90% limit from the cumulative distribution on one hand (the lower value) and the mean value of the probability distribution on the other hand (the higher value).
- Only the 90% cumulative limit for the less explored part is presented because of the great uncertainty associated with that estimate.
- The volumetric assessment results are based on a 50 year utilization period, e.g. to take into account past utilization and a prolonged development period for the whole region. A shorter period would necessitate applying a smaller recovery factor.
- The capacity estimate based on the lumped parameter modelling assumes a reservoir pressure decline less than 30 bar with full reinjection of separated brine. Thus the capacity of the Northeast sector is estimated to be about 50% greater than that of the East sector.
- In addition the generation capacity of the Domes is assumed to approximately equal to the average of the capacities of the East and Northeast production fields estimated through the lumped parameter modelling.
- The predictions of the numerical model, which only involve the heavily explored part of Olkaria (where data for calibration purposes are available), indicate a generation capacity of about 185, 155 and 240 MW_e for the East, Northeast and Domes production sectors, respectively.

The results for the heavily explored part of Olkaria, deduced by the different assessment methods (Table 3), are quite comparable, which adds confidence to the results. The outcome of the numerical model is e.g. in the middle of the range for the results of the volumetric assessment. In addition the numerical model results are fully comparable with the results of the lumped parameter model predictions. Therefore a combined generation capacity estimate of 630 MW_e for the heavily explored and peripheral parts of KenGen's concession area in Olkaria is assumed, as well as the estimate of 300 MW_e for the less explored parts. This is based on the 580 MW_e capacity estimate of the numerical model and the lower limit of the capacity estimate for the peripheral zone, 50 MW_e. The estimate includes the 430 MW_e already utilized and under implementation.

TABLE 3: Electrical generation capacity estimates for the Greater Olkaria Geothermal System obtained during the present Optimization Study. See text for various relevant premises of the estimates

Area/sector	Assessment method	Generation capacity (MW_e)	Classification[1)]	Comments
Heavily explored Part	Volumetric method	520 – 670	Proven reserve	Includes plants in operation w. 150 MW_e capacity
	Lumped modelling	~600[2)]		
	Numerical model	580		
Peripheral zone	Volumetric method	50 – 150	Probable reserve	
Less explored Parts	Volumetric method	>300	Inferred resource	***To be confirmed by surface exploration and exploration/ appraisal drilling***
Total		870 – 1120		

1) Australian Geothermal Code Committee (2008)
2) Assuming a generation capacity for the Domes approximately equalling the average of the capacites of the East and Northeast production fields estimated through lumped parameter modelling

KenGen estimates that steam corresponding to approximately 440 MW_e has become available in the Olkaria East and Olkaria Domes sectors, as of the middle of 2012, through production wells drilled during the intense drilling activity in progress since 2007, as already mentioned. This may be interpreted as indicating that only about 40 MW_e more are needed to reach the 630 MW_e capacity of the heavily explored and peripheral parts of Olkaria, referred to above. The situation is not so simple, however; of course one needs to keep in mind that these results are based on individual testing of new wells for a relatively short period. It is prudent to assume that the production capacity of individual wells will decline once all the wells needed for a given generation unit are put on-line simultaneously, e.g. due to reservoir pressure decline and pressure interference.

3.6 Field development plan and reinjection

The optimization study for KenGen's concession area in the Olkaria geothermal field also included proposing a field development plan for the possible expansion of electricity generation in the field. The quantitative basis for the plan is of course the most reliable and recent estimates of the generation capacity of the geothermal system (see above) whereas drilling targets are founded on the most recent conceptual model, reviewed above. The development plan proposed is based on the division of the KenGen concession area in the two parts on the basis of knowledge on the underlying resources, already mentioned.

The development plan for the heavily explored part is based on a generation capacity estimate of about 630 MW_e for 30 years as well as the revised conceptual model of the geothermal system, with particular emphasis on permeable structures, exploitable temperature and indications of heat sources. It is estimated that about 86 production, reinjection and make-up wells are needed to attain the estimated 630 MW_e capacity, in addition to existing stand-by wells already drilled. They are assumed to be capable of yielding about 390 MW_e in the long-term (based on KenGen in-house data). New production wells may be drilled as in-fill wells, mainly in the Domes but also in the Northeast sector and as step-out wells in the peripheral zone.

The development plan for the less explored part involves a proposal for comprehensive surface exploration (e.g. complete TEM/MT-resistivity surveying) and further research before development for generation begins. The development plan proposal includes about 16 new exploration/appraisal wells in this part as well as approximately 10 pressure monitoring wells throughout the whole area.

Reinjection of all separated brine, as well as a substantial part of the steam utilized for electricity generation after condensation, is foreseen as crucial in the future development of the Olkaria geothermal resource, mainly for the purposes of mass balance preservation and reservoir pressure maintenance, but also for environmental reasons. Predicting the overall effect of different long-term reinjection scenarios with the numerical model of the Olkaria geothermal system turned out to be quite uncertain and poorly constrained because of lack of data to calibrate reinjection sectors away from the current production zones, as well as their connections to the production sectors.

Some of the main issues that need to be resolved in order to optimize future reinjection in Olkaria are (i) how much of the mass extracted should be reinjected, or actually how much steam condensate (since all brine is expected to be reinjected), (ii) where the reinjection should be located, (iii) at what depth should the reinjection be focussed, (iv) what is the benefit of increased reinjection in terms of fewer make-up wells needed and (v) how detrimental is the lower injection temperature associated with condensate injection? The numerical model can only partly resolve these issues.

A certain very clear result can be seen, however, through reinjection scenario modelling of the heavily explored part of Olkaria. This is the fact that the benefit of reinjection beyond that of separated brine is quite limited and that the need for make-up wells does not decrease with increased reinjection. This appears to be a result of the nature of the heavily explored parts of the geothermal system as simulated by the model, which causes the increased mass discharge from production wells due to increased reinjection to be counteracted by reduced enthalpy, because of how close reservoir conditions are to boiling. The reinjection modelling furthermore indicates that deep (~2000 m) reinjection is more advisable, as a general rule, and confirms the contention that the temperature of reinjected fluid is not an issue as such. The latter is because the rate of the so-called cold-front propagation from a reinjection well to near-by production wells is not dependent on the temperature, but rather on the properties of flow-paths connecting the wells and the rates of reinjection and production.

It is likely that reinjection in Olkaria will need to be in line with the general idea of reinjecting on the margins of the most productive parts of the geothermal system rather than in-between production wells, because of the expected scale of the reinjection and associated cooling risk. As reinjection will increase in coming years the opportunity should be used to conduct comprehensive reinjection research. This research should include a comprehensive program of tracer testing, with associated analysis and modelling. A long-term reinjection plan for Olkaria must also be seen as dynamic and flexible.

4. CONCLUSIONS AND RECOMMENDATIONS

The conceptual model of the Greater Olkaria Geothermal System, which originally dates back to the middle 1970's, has been revised based on all available geological and geophysical information, temperature and pressure data, various reservoir testing and monitoring data as well as information on the chemical content of reservoir fluids. Most important are data from about 60 deep wells drilled in the area since 2007. Consequently the electricity generation capacity of the geothermal system was assessed on the premises that the resource should be split in two parts; a heavily explored part where extensive drilling has delineated the resource and long-term utilization experience exists and a less explored part where drilling has been limited and mainly indirect indications on an exploitable resource exist. The generation capacity estimates for Olkaria are based on the results of three reservoir assessment methods; (i) volumetric capacity assessments for both the heavily explored and less explored parts, (ii) lumped parameter modelling of the pressure response of Olkaria East and Northeast, and (iii) the predictions of detailed numerical model for the heavily explored part. The numerical model is by far the largest and most comprehensive model developed for the system so far. The results obtained through applying the different assessment methods for the heavily explored part of Olkaria are quite comparable, which adds confidence to the results.

Various recommendations have been put forward as part of the optimization study this paper is based on. These will not all be repeated here, but the following should be emphasised:

(1) This study has revealed the great importance of a comprehensive monitoring program for geothermal systems being utilized, in particular production and pressure decline monitoring. Monitoring of other aspects, such as chemical content and flowing enthalpy, is of course also of great importance. The considerable scatter in available reservoir pressure monitoring data, for both production sectors, reveals the need for a more focussed reservoir pressure monitoring program for Olkaria, which can e.g. be improved through both selection of appropriate monitoring wells distributed throughout the Olkaria area and through a sufficient monitoring frequency.
(2) The pressure response of the East production sector indicates substantial recharge to the geothermal system. Repeated micro-gravity monitoring provides an efficient way of quantifying the mass balance in geothermal systems, i.e. the balance between mass extraction, reinjection and natural recharge. Such monitoring has to some extent been conducted in Olkaria.
(3) A great increase in electrical generation by KenGen in Olkaria is expected within the next few years, with an associated drastic increase in mass extraction. Carefully monitoring the eventual effect of this increase provides the most important information on which to base further expansion of generation in Olkaria. Realizing future expansion in appropriately sized steps provides a continuous opportunity for such monitoring.
(4) The numerical model, which has now been developed for the Olkaria Geothermal System, can become an indispensable management tools during long-term utilization. The same applies to the lumped parameter models, which can easily be upgraded as more pressure monitoring data become available.
(5) The experience in Olkaria III, where 100% reinjection is applied, should be used to help planning future reinjection in KenGen's concession area in Olkaria.

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