PROCEEDINGS, 42nd Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, February 13-15, 2017
SGP-TR-212

Geothermal Resource Assessment of Alaşehir Geothermal Field

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Keywords: Alasehir, Turkey, resource assessment, heat in place

ABSTRACT

Alaşehir geothermal area located in Alaşehir Graben, West Anatolia – Turkey is the current target for geothermal field development. Currently, more than 6 operators are developing the power capacity in this field on a strictly competitive, and largely confidential, basis without significant exchange of resource information among them. Although there are three binary and a combined flash-binary power plants with widely changing power generation efficiency between plants, additional new plant capacity will be installed before 2020 due to attractive geothermal incentives. Power supply capability of the field is discussed considering economic and physical reliability using heat in place method. Discussions on the performance of the field is also included using different development scenarios.

INTRODUCTION

Although there are several methods used for assessing energy that can be extracted from a geothermal reservoir, only the volumetric methods and reservoir simulation are adequate. Since reservoir simulation requires several important input data, that are usually unavailable especially at the early exploration and delineation stages of geothermal reservoir development, volumetric reserve estimation method introduced by the U.S. Geological Survey (Muffler, 1978), modified to account for uncertainties in some input parameters by using a probabilistic basis (Monte Carlo simulation) is used to estimate geothermal energy reserves. This technique is based on a volumetric calculation of the heat-in-place at a project area, with reasonable assumptions made about the percentage of that heat that can be expected to be recovered at the surface and the efficiency of converting that heat to electrical energy (Equation 1 and 2). The heat-in-place calculation takes into account only a volume of rock and water that is likely to contain adequate permeability and temperature for the generation of electricity using contemporary technology. In this regard, hot rock that is deeper than likely to be economically drillable in a contemporary commercial project is not included. The term “geothermal reserves” is different from the overall “geothermal resource,” which includes all heat underground. The “geothermal resource” is further subdivided into “inaccessible” by current drilling equipment and “accessible” (likely to be drillable in the ‘foreseeable’ future). The “accessible” resource is further subdivided into “residual” (too deep for present economics) and “useful” (perhaps drillable at currently acceptable cost). Finally, “useful” is subdivided into “sub-economic” (probably too deep, especially if the resource temperature is not very high, or displaying inadequate permeability), and “economic” (considered likely to be viable) (Muffler, 1978).

$$MW_e = \frac{E * RF * CE}{PL * LF} \tag{1}$$

$$E = (1-\phi)c_r\rho_r Ah\,(T_r - T_u) + \phi c_f\rho_f Ah\,(T_r - T_u) \tag{2}$$

The volumetric method refers to the calculation of thermal energy in the rock and the fluid that could be extracted based on specified reservoir volume, reservoir temperature, and reference or final temperature that is based on the ambient temperature, following the exhaust pressures of the turbines. Many, however, choose a reference temperature that could be described as equivalent to the minimum or abandonment temperature of the geothermal fluids for the intended utilization of the geothermal reservoir. For example, for direct heating applications such as space heating the abandonment temperature is typically 30-40°C but for electricity generation the reference temperature is usually 180°C for conventional flash power plants but as low as 130°C for binary plants (Sarmiento and Steingrimsson, 2011). The reserves are considered as proven if the portion of the resource sampled by wells demonstrates reservoir conditions and substantial deliverability of fluids from the reservoir (Clotworthy et al, 2006 and Lawless, 2007). On the other hand, probable reserves are unproven reserves that are most likely recoverable, but are less reliably defined than the proven reserves but with sufficient indicators of reservoir temperatures from nearby wells or from geothermometers on natural surface discharges to characterize resource temperature and chemistry. Possible reserves have slighter chance of recovery compared to the probable reserves but surface exploration, such as hot springs, fumaroles and resistivity anomalies may show that a reservoir exists.

In the Monte Carlo simulation method of calculating geothermal reserves, some parameters in equations 1 and 2 are assigned fixed values, and others are assigned ranges of values believed to be likely, on the basis of available information about the resource. These ranges may include only a minimum and a maximum, or may also include a most-likely value as in triangular distribution. Parameters like reservoir area, depth, thickness, temperature and recovery factor usually vary substantially from case to case, whereas, other parameters including volumetric heat capacity, rejection temperature, conversion efficiency, plant or project life and plant load factor can be specified sufficiently accurately using available engineering data. As pointed out by Garg et al (2011) the “available work” of

USGS methodology is a strong function of the reference temperature, and that the utilization factor (i.e. ratio of electric energy generated to available work). The conversion factor recommended by USGS method ranges from 0.4 - 0.45; however relatively lower conversion factors (0.13 - 0.15) are observed due to resource characteristics and economic considerations.

ALAŞEHIR GEOTHERMAL RESERVOIR

Alaşehir geothermal area that is located in southern part of the Alasehir Graben (also known as Gediz Graben) in western Turkey is one of the most important geothermal areas. The Alasehir Graben is situated approximately 140 km east of Izmir in the Western Anatolian extensional province (Dewey and Sengor, 1979). Both the southern and northern margins of the Alasehir graben are dominated by non-marine sediments that show marked lateral and vertical facies variation (Purvis and Robertson, 2005). The Alaşehir Graben contains four sedimentary units developed under an extensional tectonic regime and is a superimposed graben containing possible traps as well as a high potential for hydrocarbon generation. The stratigraphy of the region is mainly represented by metamorphic rocks of the Menderes Massif and the synextensional Salihli Granitoid as basement rocks, which are tectonically overlain by Neogene-Quaternary aged sedimentary rocks. These rocks are cut by detachment faults, which are also cut by younger various high-angle normal faults. The graben fill is composed of four sedimentary units (Figure 1): Alaşehir formation, overlain by Kurşunlu and Kalatepe formations, and finally alluvium at the top (Iztan et al, 1991; Seyitoglu, 1992 Seyitoğlu et al, 1994; Seyitoğlu and Scott, 1996; Yazman, 1995; Yazman et al, 1998; Yılmaz and Gelişli, 2003). Basement is composed of carbonates of Menderes Massif rocks. They are highly fractured and karstified so that they are important to be geothermal aquifer. Menderes massif rocks are schists, quartzites, phyllites and marbles. Especially, marble and schist with alternating micaschists are dominantly observed in the reservoir. Apart from marble and schists, calcschist, gnesis and quartzite are observed as well.

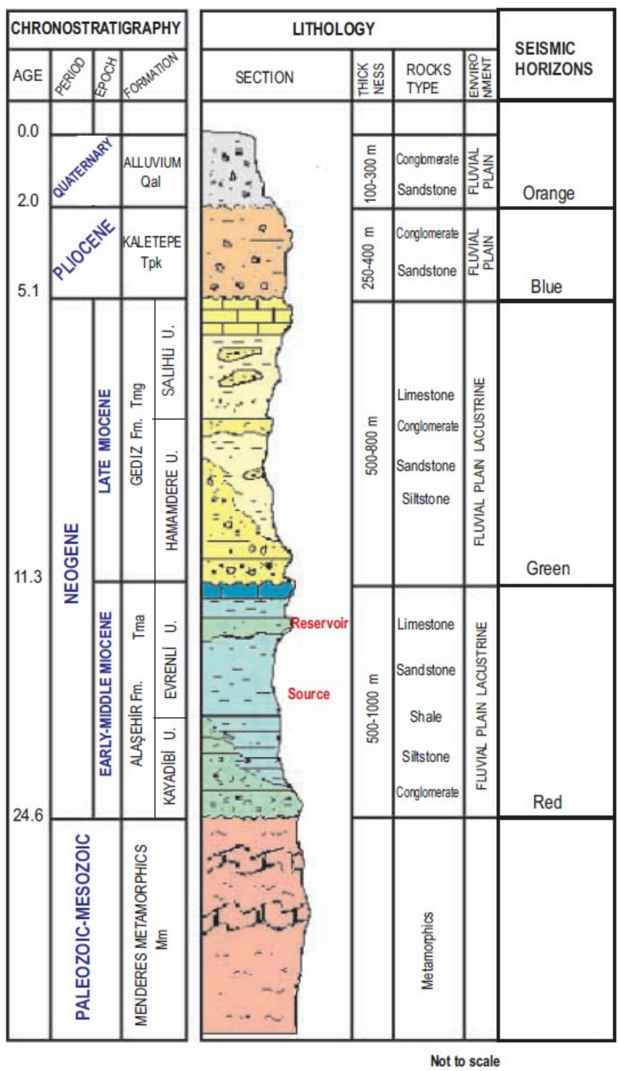

Figure 1: Generalized stratigraphic column of the Alaşehir area (After Yilmaz and Gelişli, 2003)

The Alaşehir geothermal field is located between Alaşehir and Salihli towns. Currently, more than 6 operators are developing the power capacity in this field on a strictly competitive, and largely confidential, basis without significant exchange of resource information among them (Figure 2). Although there are three binary and a combined flash-binary power plant with widely changing power generation efficiency between plants, additional new plant capacity will be installed before 2020 due to attractive geothermal incentives. In the southern part of the graben, there are several deep wells whose depths vary between 1100m to more than 2500 m (Akın et al, 2015). The high temperature (> 190°C) geothermal reservoir in the upper section of the Paleozoic basement feeds from zones in the carbonaceous metamorphics at approximately 1150 m and 1600 m depths. The reservoir has good permeability-thickness probably from intersecting fractures. The southern part of the reservoir is liquid dominated with 2% to 4% CO_2 by weight suggesting that the gas breakout pressure is between 90 and 115 bara corresponding to a gas breakout depth between 800 to 1200m, depending on the well flow rate that change between 220 ton/hr to 635 ton/hr. Well depths reach to more than 3000 m near the center of the graben. In this part, the highest recorded bottom hole temperature is 251°C at a depth of 3011 m. The average flow rate is 300 ton/hr suggesting a similar permeability-thickness that has been observed in the southern part.

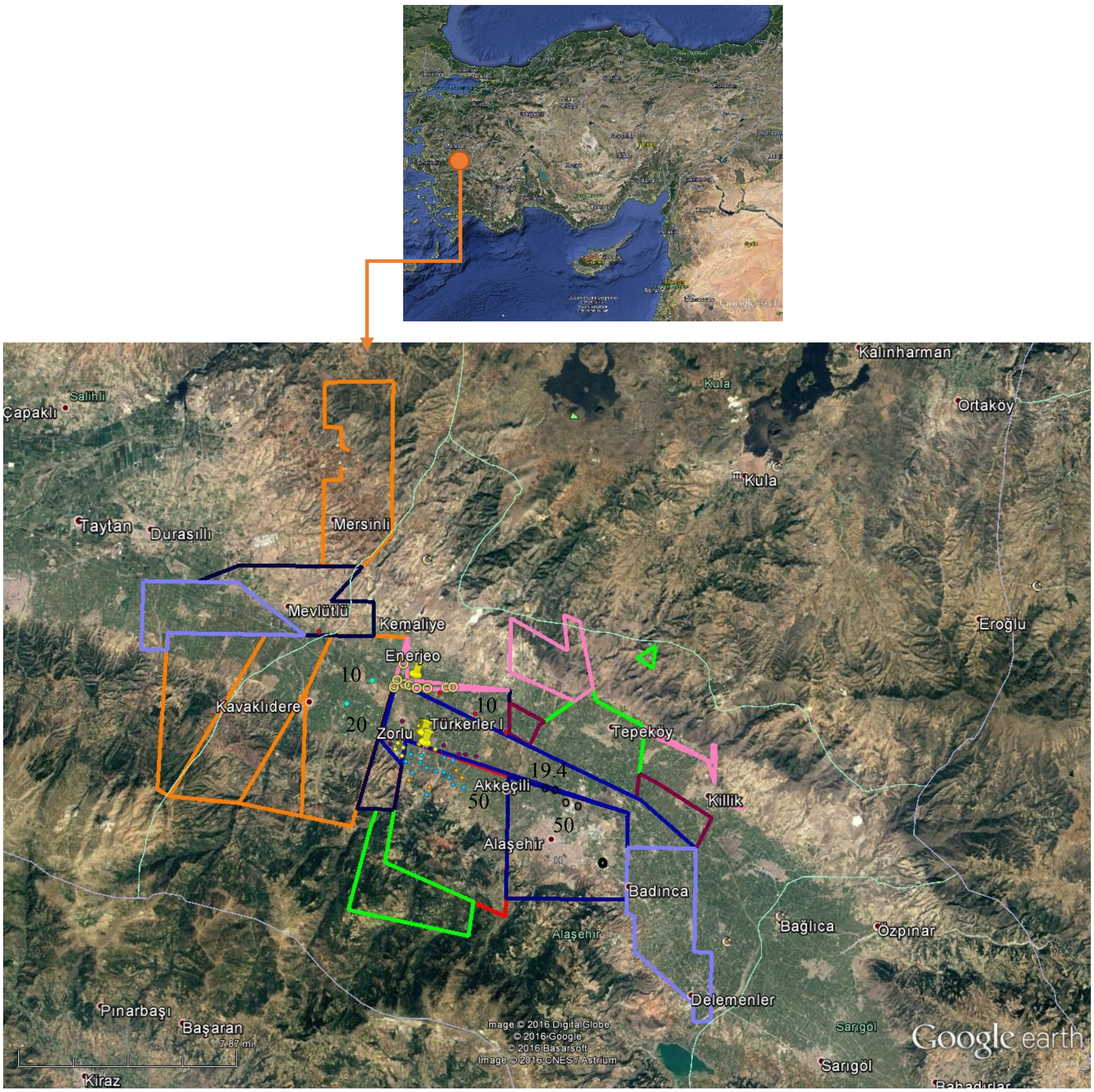

Figure 2: Geothermal licenses, power plants and well locations in Alaşehir geothermal area.

RESOURCE ASSESSMENT

Two resource assessments were carried out: at the exploration stage when only two wells at the southern section were present and at when there were more than 50 wells have been drilled (Figure 2). Both assessments were carried out using the aforementioned volumetric method. In the exploration stage estimates of reservoir temperatures ranged from a minimum of 193°C based on the measured flowing temperature to 217°C based on quartz geothermometer. Based on two wells, the size of the reservoir was difficult to estimate. During the exploration stage, it was envisioned that the tectonic and geologic setting was consistent with a fairly narrow but perhaps extending deep and possibly along the strike of the graben bounding fault system. Despite uncertainties in the temperature and size of the field, an estimate of resource capacity was performed using a heat-in-place model. The computed probability distribution showed that there is a 90% probability that the electric generation capacity is at least 5.9 MWe and a 10% probability that the electric generation capacity is ~32.9 MWe for 30 years. The median (50 percent probability) generation capacity is ~15.1 MWe.

Table 1. Input parameters for Monte Carlo simulation at the exploration stage.

Parameter	Minimum	Maximum	Data Source
Reservoir area, km^2	1	6	Conceptual model and geophysics
Reservoir thickness, m	500	1500	Conceptual model
Reservoir depth, m	1050	1050	Well log
Reservoir temperature, °C	193	217	Downhole temperature measurement and geothermometer
Volumetric heat capacity, kJ/m^3-K	2620	2620	Typical value
Rejection temperature, °C	40	40	Condenser temperature
Conversion efficiency	0.125	0.125	Typical value
Plant life, years	30	30	Estimate
Load factor	0.95	0.95	Typical value

Following this assessment more than fifty wells have been drilled at various locations (Figure 2). The highest reservoir temperature was 251°C at a depth of 3011 meters at the eastern section of the graben. It was observed that reservoir temperature decreased then increased to more than 250°C from east to west. Based on the findings observed in the new drilling logs the assessment has been re-conducted. This time volumetric estimation in the Alaşehir geothermal area defined the lateral and vertical resource boundaries on the basis of the ability of many wells to flow unaided at a minimum required temperature of 170 °C. Wells were recently observed to sustain commercial flow rate at this temperature, after the field had been produced sufficiently. The wells were drilled to intersect temperatures of at least 170 °C at shallower levels of the reservoir as the fluid has the ability to flow to the surface. The porosity was assigned a log normal distribution following the observations of Cronquist (2001) quoting Arps and Roberts (1958) and Kaufmann (1963) giving that, in a given geologic setting, a log normal distribution is a reasonable approximation to the frequency distribution of field size, i.e., to the ultimate recoveries of oil or gas and other geological or engineering parameters like porosity, permeability, irreducible water saturation and net pay thickness. The mean and the standard deviation are however needed to be defined. All other parameters like fluid densities and specific heat were dependent on temperatures (Table 2).

Table 2. Input parameters for Monte Carlo simulation at the delineation stage.

	Scenario I		Scenario II	
Parameter	**Minimum**	**Maximum**	**Minimum**	**Maximum**
Reservoir area, km^2	41.6	94.69	41.6	232.32
Reservoir thickness, m	500	1500	500	2750
Reservoir depth, m	750	2380	750	3500
Reservoir temperature, °C	170	230	170	250
Volumetric heat capacity, kJ/m^3-K	2620	2620	2620	2620
Rejection temperature, °C	80	80	80	80
Conversion efficiency	0.125	0.125	0.125	0.125
Plant life, years	30	30	30	30
Load factor	0.95	0.95	0.95	0.95

Chemical geothermometers are methods of estimating quantitatively the temperatures of water- rock reactions at depth. The most widely- used and reliable geothermometers use concentrations and ion ratios among Na, K, Ca, and Mg, and concentrations of silica (SiO_2). If water temperatures are genuinely high (more than about 150°C) these geothermometers can be quite accurate, with the standard deviation of uncertainty being about ±20°K (Verma, 2013), but if the waters have partly re- equilibrated during a slow ascent, or have mixed with shallow ground waters (or drilling fluids), there can be differences between geothermometers that require careful evaluation and cannot always be resolved. Na/K and Na- K- Ca temperatures tend to best represent chemical equilibrium conditions at depth, whereas temperatures that consider Mg (K- Mg and Na- K- Ca- Mg) and SiO_2 tend to reflect adjustments during cooling. At northwestern section of the graben, estimated geothermometer temperatures (Bülbül et al, 2011), particularly silica-based, were consistent with measured (flowing dynamic) reservoir temperatures but lower than maximum static temperatures, suggesting that the main flow is not from the highest measured temperature zones. Reservoir temperatures estimated from geothermometers from well samples at the southern section of the graben indicated that high temperatures (>250°C) are present in the deeper zones (Yıldırım, 2016). At the eastern part of the graben geothermometer based reservoir temperatures are as low as 150°C (Yılmazer et al, 2010).

The proven area was selected such that it is defined by drilled wells with at least 500 meters beyond the drainage of the outermost wells bounded by an extrapolated production temperature of 170°C, enclosed by good permeability and demonstrated commercial production from wells (Figure 3). The probable area was defined by wells with temperature contours that would extrapolate to an average temperature of 190°C to the edge of the field. Areas currently inaccessible because of limited rig capacity and restriction imposed within the boundaries of concession area, areas with wells which could be enhanced by stimulation like acidizing by work-over of wells, other treatments or procedures which have been proven to be successful in the future and areas with extensive surface manifestations where geothermometers indicate consistent or constant temperatures 170°C were included. Possible area included those not yet drilled but enclosed by geophysical measurements like Schlumberger electrical resistivity and magneto-telluric surveys, defined by areas with thermal surface manifestations, outflow zones, high postulated temperatures based on geothermometers. Using these definitions (or rules) the minimum area changed between 41.6 and 232.32 km^2.

Proven depth was defined as the depth between the Paleozoic Menderes metamorphics levels and the maximum drillable depth of the rig that has demonstrated commercial production (Figure 3). It was observed that producing zone depths were several hundreds of meters deeper in the north end of the graben. Average reservoir depths of southern wells were 1491.5 meters compared to 2035 meters of the northern section wells. Note that maximum depth should have at least 170°C to warrant commercial output of the well. Probable depth was defined as the depth that demonstrated productivity in nearby areas or adjacent wells. Depth beyond the deepest well drilled in the area +500 meters provided projected temperatures reached at least 190°C at the bottom. Finally, the possible depth was defined by demonstrated productivity in nearby areas or adjacent wells (Figure 4).

Reservoir thickness is evaluated from drilling data, resistivity data and seismic data. Average thickness of drilled reservoir section changed between 28 and 1401 meters (Figure 4). Note that the measured thicknesses of the reservoir rocks as obtained from associations in the logs are much less than their true thicknesses. The reason for this is the intense normal faulting that makes it impossible to measure a complete section without a gap. As a result, measured reservoir thicknesses were utilized only as data to characterize reservoir sections around wells. On the other hand, resistivity (Gürel, 2016) and seismic data suggested a reservoir thickness changing between 450 – 1000 meters and 750 – 1750 meters. Thickness of the reservoir rocks depict distinct thickness and grain size decrease from south to north (Çiftçi and Bozkurt, 2009). Accordingly, aforementioned formations display south to north facies change and decrease of thickness that emphasizes the southern horst block as the main site of sediment supply.

Recovery factor was obtained using a correlation proposed by Muffler (1978). This correlation states that recovery factor is 2.5 times the value of porosity. Wells drilled in southern section of the graben have higher flow rates compared to those located in north and northeastern sections, possibly due to higher fracture permeabilities in these sections. Thermal conversion efficiency was selected using Nathenson (1975) and Bodvarsson (1974) correlations. These correlations are in agreement with average conversion efficiency obtained for ORC binary power plants operating in western Anatolia in Turkey. Using these values, the two geothermal resource assessment has been conducted. For the optimistic scenario every parameter that influence the power capacity is optimistically selected. As a result, proven, possible and probable power generation capacities were calculated as 270.9, 589.46 and 1223 MWe for 30 years. For the pessimistic scenario computed probability distribution showed that there is a 90% probability that the electric generation capacity is at least 103.75 MWe and a 10% probability that the electric generation capacity is ~335 MWe for 30 years. The median (50 percent probability) generation capacity is estimated to be 182.69 MWe.

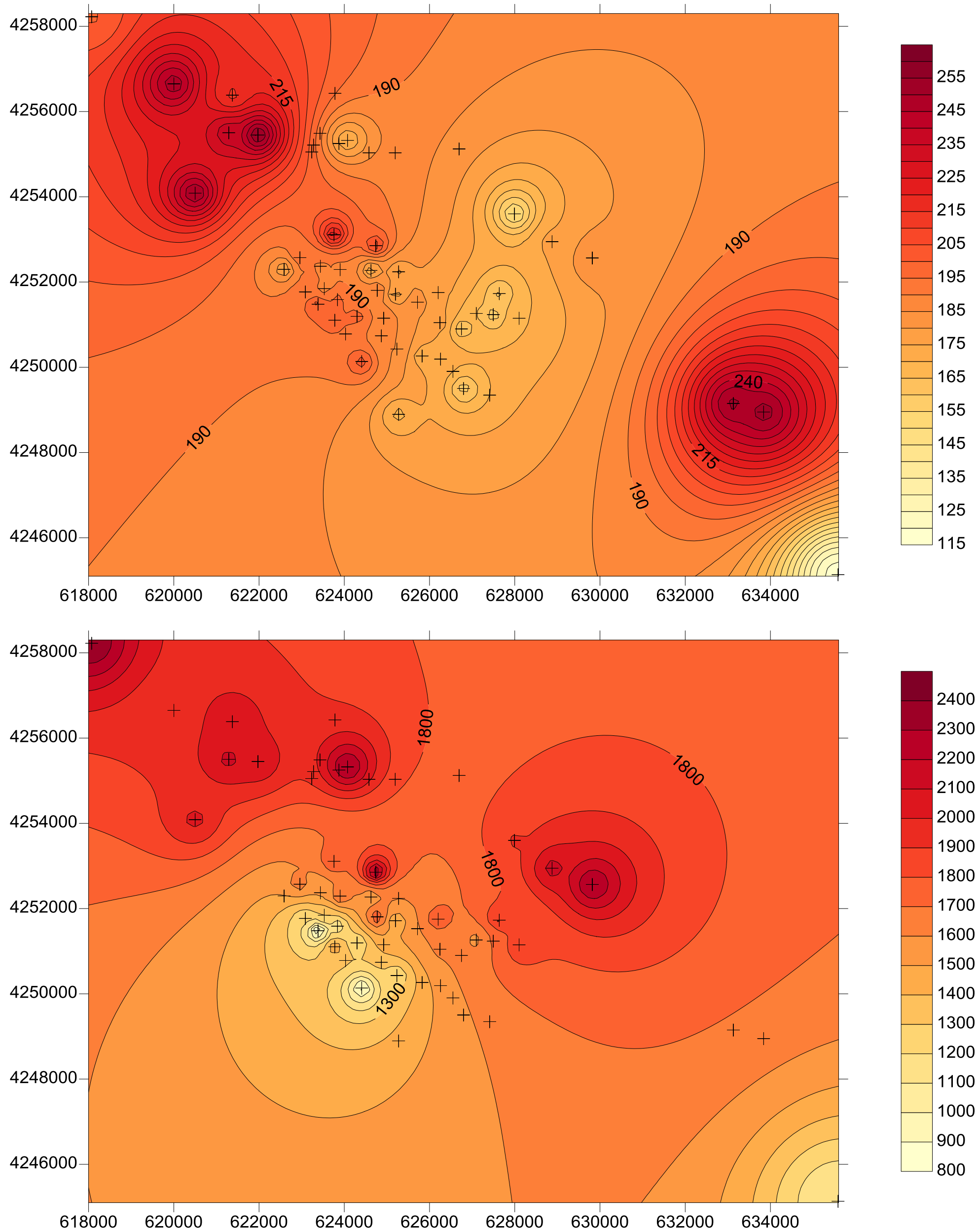

Figure 3: Bottomhole temperature of wells (°C, top) and reservoir depth (meters, bottom) in Alaşehir geothermal area.

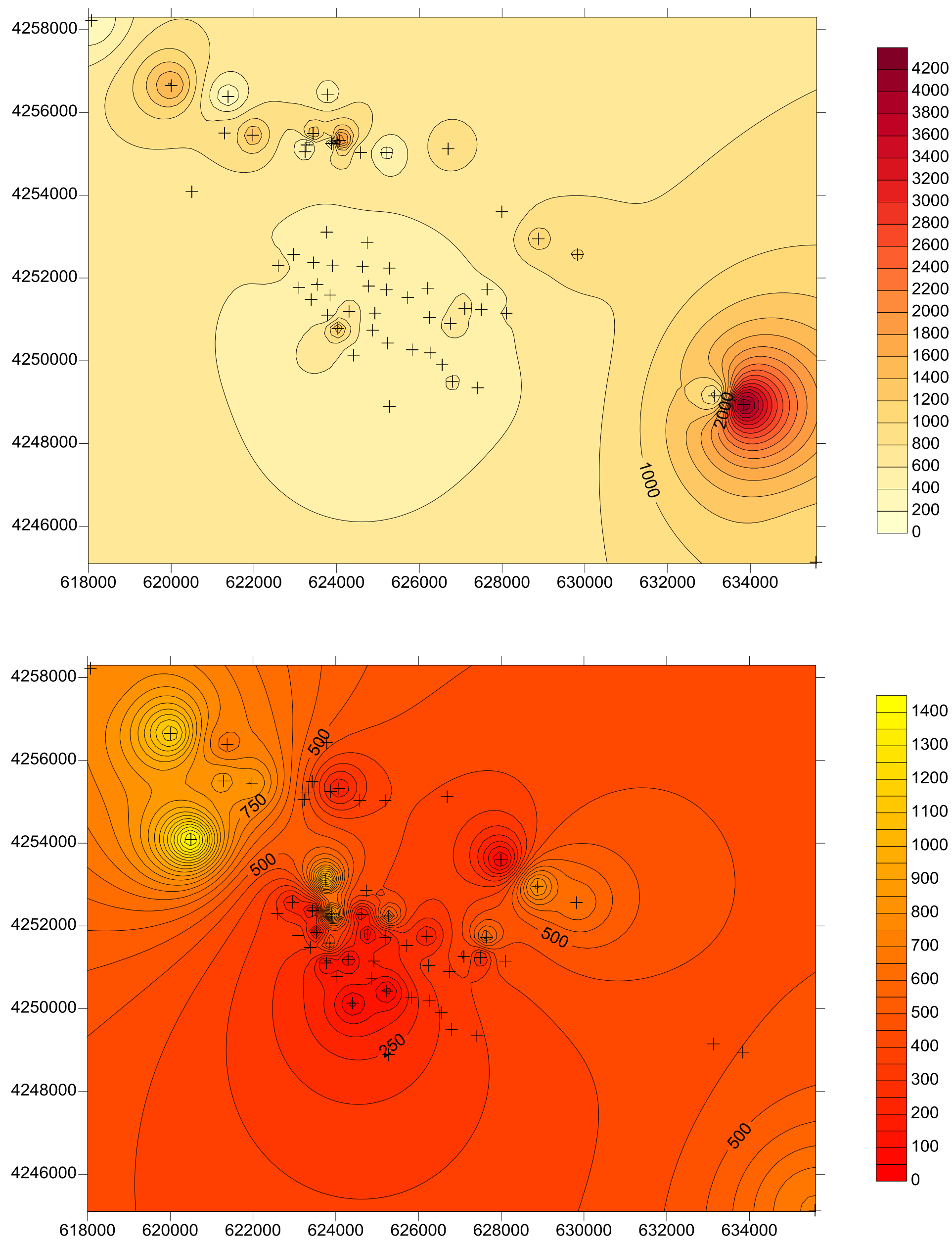

Figure 4: Well spacing (meters, top) and reservoir thickness from drilling data (meters, bottom) in Alaşehir geothermal area.

DISCUSSION

Law on Geothermal Resources and Natural Mineral Waters (No: 5686, Date: June 3, 2007) and its corresponding Implementation Regulation (No: 26727, Date: December 2007) has accelerated development of geothermal resources in Turkey. Pursuant to the Council of Ministers Decree No. 2013/5625, the generation facilities, which will be, operational by 31 December 2020 and holding a renewable energy resource certificate will benefit from an incentivised feed-in tariff as set forth in Schedule 1 of the Renewables Law. The feed-in tariff, which is 10.5 USD cent/kWh for geothermal electricity guarantees 10 years of power purchase following the commencement of the operations of the generation facility. Due to these attractive incentives several licenses have been acquired by different operating companies. Unfortunately, these licenses seem to have no relationship to geology or geothermal potential. Currently, two identical ORC binary power plants with 24 MWe gross capacity were commissioned in southern part of the graben (Figure 2). In the neighbor concession a 45 MWe double flash plus an ORC binary power plant has been build. The first ORC power plant has been operational since 2014. The double flash power plant has been commissioned in 2015. The last ORC power plant located in the northern section of the graben with 24.9 gross capacity is operational since May 2016. Total installed capacity will be further increased by binary plants and a flash power plant that will be built before 2020. Two of these (10 MWe and 20 MWe capacity) will be commissioned in the western part of the geothermal area, whereas a 10 MWe one will be commissioned in northern section and two 50 MWe capacity power plants will be built in southeastern and eastern sections along the graben (Figure 2). Total installed power will be 257.9 MWe by the end of 2020, which is slightly below the proven power using optimistic Monte Carlo simulation scenario. Note that, heat in place calculations assume that geothermal field and the power plants are optimally operated. The recovery factor used in the aforementioned calculations have not been validated yet. Although there seems to be enough geothermal power, stored heat especially in the optimistic scenario may overestimate field capacity due to reasons discussed below.

Resource assessments of the aforementioned license areas were independently carried by the operator companies. The total flow of the drilled wells has sometimes been incorrectly taken as the field capacity. As a result, several unnecessary wells creating interference effects between themselves and between license areas have been drilled. Well spacing in northern part of the geothermal area where 24.9 MWe capacity is operational, is extremely small, 168 – 214 meters (Figure 4). Well spacing increases to more than 500 meters at the southern development licenses. However, a recent tracer test conducted in the southern part showed that production and injection wells located in neighboring leases are in communication, creating interference effects between injection and production wells. It is very likely that interference in northern wells are much higher due to smaller well spacing. A recent study conducted to find out relation between well spacing and net present value in geothermal doublets showed that minimal required well spacing is dependent on the reservoir thickness, flow rate and the allowed production (Willems et al, 2016). In this regard, simulation studies are required to further comment on well spacing in Alaşehir geothermal area.

Yet another problem is the sustainability of reservoir pressure due to the necessity of producing and injecting within the same license area due to aforementioned geothermal law. Most of the power plants are built without long term tests as water discharge in the area is very limited due to environmental concerns. As a result, most of the wells are operated at high rates due to financial commitments. In these oversized projects, with high extraction rates the energy yields are high but the energy delivery will decrease significantly with time, and can cause the breakdown of a commercially viable operation. One other possible outcome of producing and injecting within the same license area and sub-optimal well spacing is short-circuiting of the injected fluid to the production wells. Fortunately, any cooling due to injection water breakthrough is reversible if the offending injector is shut down. The mitigation plan should be based on a calibrated numerical model using the cooling history and the results of a properly executed tracer test.

Consolidation or merger of all interests in Alaşehir geothermal area, in other words, unitization of the geothermal leases (Tureyen and Satman, 2013) seems to be a solution for a sustainable geothermal production. In this regard, wells can be drilled on the basis of geology instead of lease lines and the area can be fully developed with fewer wells. In unitized situations drainage is not a problem since fewer wells are drilled. Further advantages include the use of common facilities, avoiding duplication of equipment, less environmental impact due to fewer wells, roads and infrastructure, and conservation of the geothermal resource due to prevention of waste, which leads to increased overall profit of leasers (Cargill and Conover, 1978).

CONCLUSION

Power supply capability of the Alaşehir geothermal area located in Alaşehir Graben, West Anatolia – Turkey is discussed considering economic and physical reliability using heat in place method. Although there are three binary and a combined flash-binary power plants with widely changing power generation efficiency between plants, additional new plant capacity will be installed before 2020 due to attractive geothermal incentives. Monte Carlo simulations based on optimistic parameters showed that there is enough geothermal power capacity to host a power total of 270.9 MWe. It was concluded that although there seems to be enough geothermal power, stored heat especially in the optimistic scenario may overestimate field capacity due to oversized projects, lease to lease and well to well interference due to sub-optimal well spacing and high extraction rates. Unitization of the geothermal leases seems to be a viable solution for a sustainable geothermal production.

NOMENCLATURE

A reservoir area, m^2

CE Conversion efficiency, ratio

c_r rock heat capacity, kJ/(kg°C)

c_f fluid heat capacity, kJ/(kg°C)

E Maximum sustainable power plant generation capacity, kJ

h net reservoir thickness, m

LF Load factor, the fraction of time the plant produces power, ratio

PL Project life, years

RF Recovery factor, ratio

T_r Reservoir temperature, °C

T_u Ambient or abandonment temperature, °C

φ Porosity, fraction

ρ_r Rock density, kg/m^3

ρ_f Fluid density, kg/m^3

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