The Comparison of Reservoir Characterizations and Operational Challenges at High Temperature Geothermal Reservoirs in Western Anatolia (Turkey) and Kenya

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ABSTRACT

Due to the remarkable developments on geothermal power generation in the last decade, Turkey and Kenya have attracted the attention of the geothermal community in the world. Turkey is located in the top four, with 56 numbers geothermal power plants and 1,600 MWe installed capacity and Kenya’s status rapidly increases to the first 5 countries with about 900 MWe at geothermal power production around the world in 2019. Geothermal exploration studies started in Kenya in 1950s and in 1960s in Turkey and the first geothermal power plant was commissioned in both countries in the 1980s. In Turkey, Western Anatolia has important high geothermal systems such as; Kizildere, Germencik, Pamukören, Salavatlı, Alasehir fields which are suitable for power production, depending on large graben structures like Buyuk Menderes and Gediz Grabens in the Aegean Extensional Zone. The reservoir type is mainly liquid dominated and the reservoir temperatures can reach to 287 °C at deep carbonate type reservoirs at Western Anatolia. In Kenya, geothermal systems are located in the Great Rift Valley of Kenya and Olkaria, Menengai, Baringo-Silali are the most important sites for geothermal power production. Multi-reservoir systems have been shown as liquid dominated at shallow depth, deep reservoirs are represented with a steam dominated geothermal system and the reservoir temperatures can exceed 340 °C at the volcanic reservoirs in Kenya’s geothermal systems. This study, is focused on the comparison of geothermal reservoir characterization with the geochemistry aspect and operational challenges of power plants with possible solutions to both Kenya’s and Turkey’s operational challenges. It is expected to perform good collaboration on geothermal solutions in both countries.
1. Introduction

The importance of renewable energy sources is increasing in the world day by day. It is clear that renewables are necessary to increase the country's self-efficacy in the modern world. The criticality of energy supply was once again observed during the Covid-19 pandemic. Geothermal energy is one of the important renewable energy sources and geothermal sources provide power, heating, cooling and different industrial application opportunities in its region. However, this energy source requires special geological conditions to occur and some parts of the world are richer in geothermal resources like Turkey and Kenya.

Turkey’s and Kenya’s geothermal power capacity growth during the last decade have been two of the fastest countries in the world (REN21, 2020; Fig 1). Turkey is ranked in the top four countries globally with geothermal power production and total installed geothermal power capacity is around 1.6 GWe for 2020 and the target set by the Turkish Ministry of Energy and Natural Resources is 2600 MWe by 2025. As in 2019, Turkey and Indonesia still remained the lead for new installations, followed closely by Kenya. Kenya has Africa’s most active geothermal power market and currently installed geothermal power capacity is around 900 MWe, while the new target is declared as 3000 MWe for 2030 (Huttrrer, 2020).

![Figure 1: Geothermal Power Capacity Additions, 2019 (REN21, 2020)](image)

Bilateral relations between Turkey and Kenya have been developed since 1963 and there are developing import and export relations such as; petroleum products, transportation machinery, textile fibers, steel, raw materials (Turkish Ministry of Foreign Affairs, 2020). It is also possible to build a new relationship on the renewable energy industry now (Cannon, 2016).

In this study, we focus on high temperature geothermal systems for geothermal power production in both Turkey and Kenya and the main aim is to reveal the needed information depending on the different reservoir types for the reservoir management between the two countries.

2. Geothermal Power Status of Turkey and Kenya

2.1 Status of Turkey

The installed electricity capacity of Turkey was around 92 GWe as of June 2020. This capacity consists of; 31.3 % hydropower, 18.1 % other renewables (wind, solar, geothermal, biomass), 28.01 % natural gas, around 21 % coal.

In Turkey, more than 460 geothermal fields have been discovered since the 1960's (Mertoğlu et al., 2020). The first high temperature geothermal field was Kızıldere geothermal field.
(Denizli city) and the first and single flash type geothermal power was commissioned in Kızıldere in 1984. As of June 2020, 56 geothermal power plants have been produced around 1.6 GWe power at 27 geothermal fields in Turkey (Fig 2). More than 1000 wells were drilled only for geothermal power production purposes (Kaya, 2017) and depth of geothermal wells can reach up to 4500 m in Western Anatolia.

Discovered high temperature geothermal systems are mainly located in Büyük Menderes Graben and Gediz Graben and a few of them can be seen in Tuzla (Çanakkale) and Afyon regions (Fig 2).

Most of the geothermal power plants use an ORC binary cycle (Fig 3), with a few using single and multi-flash (double and triple) or advanced systems (flash+binary). Most of the power investors prefer to install ORC binary type geothermal power systems due to reservoir temperatures and operational issues in Turkey. However, in summer time, the efficiency of air-cooled binary ORC type geothermal power systems decrease because of over than 35 °C air temperature in Western Anatolia. Beside binary systems, there are three triple flash systems, which are also combined cycle with binary units and one single flash system in Kızıldere geothermal field and a few double flash cycles in Germencik geothermal field and one double flash+binary cycle in Alaşehir geothermal field in Western Anatolia.
Turkey has feed-in-tariffs for renewable energy power plants under the Renewable Energy Resources Support Mechanism (YEKDEM) between 2005-2020 and this tariff system has significantly supported the renewable energy market in Turkey.

2.2 Status of Kenya

Based on the GDP data, Kenya is the largest economy in East Africa and power-generation capacity is around 3 GWe. 27% of this capacity is being fossil fuel power plants and rest of it provides from renewables such as geothermal, hydropower and recently wind and solar. It is reported that 64% of the population can access electricity and decentralized energy systems are under project status for the rural regions in Kenya (Omenda et al., 2020; Girona et al., 2019; Fig 4).

There are four main geothermal project areas as; Olkaria, Menengai, Baringo-Silali, Suswa in Kenya (GDC, 2020; Fig.5). Geothermal exploration studies started in Kenya in 1952 (KPLC, 1992). After the 1970's geothermal exploration studies started to accelerate by a UNDP-Government of Kenya joint project. Firstly, Olkaria region was explored with detail and the first unit of Olkaria-1 15 MWe single flash geothermal power plant was commissioned in 1981 and after capacity building studies, the capacity increased to 45 MWe in 1985. In 2014, 140 MWe 2 single flash units were added to the Olkaria-1. The capacity building studies still continue for this region (Mangi, 2018).

Olkaria-2 single flash GPP was commissioned with 105 MWe capacities in 2003. Respectively, Olkaria-3, Olkaria-4, Olkaria-5 GPPs put in use as single flash and binary type power plants with capacity building studies in Kenya. The last one; Olkaria-5 commissioned in 2019 and consists of 2 units and total installed capacity of the plant is 165.6 MWe. There are also three back-pressure GPPs in Kenya (Bertani, 2016).
Geothermal total installed capacity is 865 MWe contributing to about 29% of total installed electricity capacity in Kenya and about 47% of electricity consumed in 2019. The installed geothermal capacity comprises 706.8 MWe (81.7%) by Kenya Electricity Generating Company (KenGen), 155 MWe (17.9%) by OrPower4, Inc and 3.6 MWe (0.4%) by Oserian Development Company Ltd (Omenda et al., 2020). The new electricity transmission and distribution structure was built with The Energy Act in Kenya in 2006. In 2008, the establishment of the Kenya Electricity Transmission Company and the Geothermal Development Company contributed to the development of the geothermal power sector in Kenya (Omenda et al., 2020).
3. Reservoir Characterizations of Turkey and Kenya Geothermal Systems

3.1 Brief Geology and Geothermal Reservoir Characterization of Western Anatolia High Temperature Geothermal System

Turkey is located on the Alpine-Himalayan orogenic belt and the country has different tectonic zones such as the North Anatolian Fault, the Eastern Anatolian Fault, and the Aegean Extension Zone. Some volcanics have been identified in the Western region of the country such as Kula volcanics and Nemrut volcanics in the Eastern region (Bozkurt, 2001). The geodynamics of Western Anatolia differ from Eastern and other parts of Anatolia and the extensional tectonics, crustal thinning and the formation of large graben systems such as Büyük Menderes Graben and Gediz Graben have been formed in Western Anatolia (Fig 2). The Büyük Menderes Graben geothermal systems generally have higher reservoir temperatures than the Gediz Graben. The maximum reservoir temperatures are recorded as 245 °C to the east (Kızıldere field) and 276 °C to the western edges (Germencik field) of the Büyük Menderes Graben, while they are between 175-185 °C at the rest of the graben (Pamukören, Sultanhisar, Köşk, Umurlu geothermal fields). The southern branch of the Gediz Graben is suitable for power production and reservoir temperatures range between 190-220 °C Alaşehir, Salihli geothermal fields except for one geothermal well (Fig 2; Tut Haklıdr and Balaban Özen, 2019). These geothermal systems are water-dominated reservoir types and multi-reservoirs can be seen in Kızıldere, Germencik and Alaşehir geothermal wells.

The Büyük Menderes Graben consists of Paleozoic aged Menderes Meramorphics and Pliocene aged sedimentary rocks, covered with a Quaternary aged alluvium (Şimşek et al.,

Figure 5: Geothermal fields in Kenya
The basement of the Gediz Graben consists of Menderes Metamorphics like the Büyük Menderes Graben and the main reservoir is Menderes Metamorphics for both graben systems (Tut Haklîdîr and Şengün, 2020). The effective brine reinjection applications have been performed at all geothermal systems.

The chemical composition of the geothermal waters shows differences based on the different dynamics such as water-rock interaction duration, pH and non-condensable gas compositions, hydrocarbon levels or sea-intrusion effects at these geothermal systems. The remarkable ion concentration variations can be seen in the Büyük Menderes Graben that thermal waters have higher $\text{SO}_4^{2-}$, lower $\text{Cl}^-$, boron ions in the east than the west in the graben, and it is thought that this is due to the sea intrusion effect in the west edge of the graben. In the Gediz Graben, the boron level is remarkably high and the chemical composition of the thermal waters of Tuzla geothermal system is different, with high Mg and extremely high Cl ion concentrations from other geothermal fields, because of interaction between the sea and thermal waters in the region (Fig 6). This water chemistry directly affects thermal water treatment, and it may cause many operational problems due to scale precipitation during the power production. The main geothermal scale minerals are $\text{CaCO}_3$, alumina-silicates in production wells and surface equipment, silica and carbonate minerals after steam separation system and stibnite in heat exchangers (Tut Haklîdîr and Balaban Özen, 2019). Prevention of mineral scaling has been addressed by chemical inhibitors and adjustment of fluid temperatures since 2009 in Western Anatolia and based on the geothermal power cycle; the scale inhibition strategy can be changed at each geothermal field. The stable isotope variation is given in Fig 7.

In Western Anatolia high temperature geothermal systems, the analyses of gas composition in steam phase show that the primary gas is $\text{CO}_2$ with 95–99 % for the Büyük Menderes Graben and the Gediz Graben geothermal reservoirs and the origin of $\text{CO}_2$ is due to the metamorphic rocks found in the geothermal reservoirs. The second important gas component is $\text{H}_2\text{S}$, whose concentration is highest at the western edge of the Büyük Menderes Graben and Gediz Graben (Tut Haklîdîr and Şengün, 2020).

![Figure 6: Piper diagram for the thermal waters at high temperature geothermal fields in West Anatolia (Tut Haklîdîr and Özen Balaban, 2019).](image)
3.2 Brief Geology and Geothermal Reservoir Characterization of the High Temperature Geothermal Systems in Kenya Rift

The geothermal systems are closely associated with the Kenya rift which is part of the East African Rift System in Kenya and most of them volcano hosted and related Quaternary central volcanoes of the rift such as; Olkaria, Eburru, Menengai, Suswa and Baringo-Silali (Omenda et al., 2020; Fig 5).

The Olkaria is the main geothermal field and it was the first geothermal power generation region in Kenya. It is noted that the heat source of the Olkaria geothermal system is shallow individual magma bodies associated with surface rhyolites (Omenda et al., 2020). The Olkaria geothermal system is characterized as two phase reservoir (85 % steam and 15 % water) and reservoir temperatures change between 250 °C and 340 °C while the depths reach to 3000 m (Mangi, 2018; Karangithi 2000; Oman, 2009). The reservoir rock is mainly hosted by trachytes and tuffs (Ngetich, 2016). During the power production, different reinjection strategies were tested such as hot brine or cold condensate reinjection (Ouma, 2009).

The Menengai is a caldera volcano within the axis of the Kenya rift and reservoir temperatures reach to 400 °C at 2000 m depth in some wells and it is called the hottest geothermal system in Kenya (Omenda et al., 2020).

The Eburru is located to the north of Olkaria geothermal field. Although the geothermal exploration studies indicated restricted resources, the reservoir temperature is around 250 °C.

The water chemistry shows that the Olkaria East and the Northeast waters are sodium-chloride type, while Olkaria West waters show bicarbonate type in the rift (Fig 8; Karingithi, 2000). Geothermal waters are depleted in $\text{SO}_4$ ion because of precipitation of sulphide minerals such as pyrite, galena, chalcopyrite (Chandrasekharana et al., 2018). With this
reason, geothermal waters have low $\text{SO}_4^{2-}$ and high $\text{Cl}^-$ ion concentrations in the Kenya rift geothermal system. The isotope compositions are given in Fig 9. The source of $\text{CO}_2$ is thought to be pre-dominantly from the magma although carbon present in the rock may contribute a little (Becky, 2014).

Geothermal waters are supersaturated with pyrite and prehnite in the Olkaria waters (Karingithi, 2000).

![Figure 8: The water types of Olkaria geothermal field (Karingithi, 2000)](image)

![Figure 9: Stable isotopes of Olkaria geothermal waters (Karingithi, 2000)](image)
4. Conclusion

Turkey and Kenya significant high temperature geothermal sources for power production and both two countries have increased their geothermal power capacities through the various government regulations after 2005.

The high enthalpy geothermal systems were formed due to the extensional tectonics in Western Anatolia, while the geothermal systems around the East Africa are part of the regional volcano-sedimentary basins that were evolved prior to the Late Cenozoic volcanic activities. The Paleozoic age Menderes Methamorphics are observed as main deep reservoirs and the reservoir temperatures can reach to 287 °C at a few geothermal systems in Western Anatolia. In the Kenya rift system, the reservoir temperatures can reach to 340 °C and 85 % of geothermal fluid is observed as steam. Both two countries use flash and binary type cycles and some critical processes are similar because of separation system.

Turkey has gained great experiences directional drilling, coil tubing operations and optimization of geothermal reservoirs and geothermal scale mitigation systems and controlling of geothermal power plants in the last decade. Kenya has great volcanic based geothermal systems and geothermal exploration studies continue in most geothermal fields for the power production.

Possible collaborations will provide mutual technology and knowledge sharing between two countries and it can be useful for more efficient and economical geothermal power investments in future.
REFERENCES


