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Review of Latest Geothermal Applications in Türkiye: A Glimpse into the Future of Renewable Energy

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ABSTRACT

With the global emphasis on sustainable and renewable energy sources, geothermal energy has emerged as a formidable contender, particularly in regions endowed with significant geothermal potential. Due to its unique geotectonic setting, Türkiye is one such region with abundant geothermal resources. This study presents an exhaustive review of the latest geothermal applications and technological innovations adopted in Türkiye.

Harnessing Türkiye's geothermal potential has evolved considerably in recent years. The review encompasses various applications ranging from electricity generation to direct-use operations such as district heating, spa facilities, greenhouse heating, and aquaculture pond heating. Technological evolution - particularly in drilling, reservoir management, and power conversion - has elevated Türkiye's position on the global geothermal stage.

Notably, advancements in binary cycle power plants, Enhanced Geothermal Systems (EGS), and low-enthalpy geothermal systems have enabled a broader spectrum of geothermal resource utilization. The ongoing research on heat pumps and their increasing domestic integration underscores the multi-dimensional potential of geothermal applications.

Furthermore, a distinct trend has been the synergistic integration of geothermal applications with other renewables, primarily solar and wind. This holistic energy approach has amplified Türkiye's strides toward energy independence and a reduced carbon footprint.

Government policies, regulations, and incentive schemes have also played a pivotal role in shaping the geothermal landscape in Türkiye. The proactive steps toward research, development, and commercialization have fostered domestic and international investments, solidifying the nation's commitment to renewable energy.

This review is a compass for researchers, energy professionals, and policymakers. It offers insights into Türkiye's current geothermal practices, challenges encountered, and the way forward. It underscores the monumental potential of geothermal applications as an energy solution and a cornerstone for sustainable development and environmental preservation in Türkiye and beyond.

1. INTRODUCTION

Geothermal energy is a resource that harnesses the Earth's heat to generate power and provide direct heating. This energy comes from the Earth's decay and residual heat from its formation. It is found in the core, mantle, and crust. Despite its potential geothermal power remains largely untapped (Johansson and Goldemberg, 2002; Günther and Hellmann, 2017; Soltani et al., 2019).

The increasing global demand for energy driven by population growth and technological advancements makes it necessary to transition towards sources that consider concerns like greenhouse gas emissions from fossil fuels. Geothermal energy is a versatile solution to meet sustainable energy needs while reducing carbon emissions (Soltani et al., 2019).

Dry steam plants, utilizing steam directly from underground reservoirs without the extraction of mineral brine, are highlighted as having potential advantages in terms of environmental impact. In contrast, flash steam plants involve the extraction of hot water or brine, raising concerns about water quality and fluid disposal. The implication is that dry steam plants, especially those not using mineral brine, may offer a cleaner and more environmentally friendly alternative compared to flash steam plants. However, the overall environmental impact depends on various factors, emphasizing the need to consider location, technology, and operational practices for a comprehensive assessment of geothermal power plant sustainability (DiPippo, 1979; DiPippo, 2012).

On the side, power plants that operate on a system, such as Enhanced Geothermal Systems (EGS), work in a closed-loop manner, substantially reducing the release of liquids and gases. While emissions from construction, transportation, and well operations in facilities contribute to exhaust emissions, these are typically minor compared to the primary sources of emissions that include wellheads, mufflers, pipeline drains, steam traps, ejector vents, and cooling towers (Gude, 2016). A life cycle analysis shown in Figure 1 illustrates that during the operation stage, which accounts for 64.7% of emissions, they exceed those generated during the construction phase at 35.3% (Hondo, 2005).

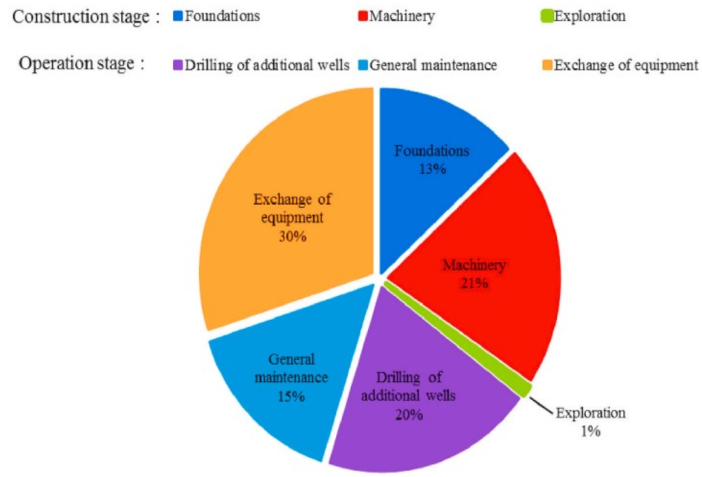

Figure 1: Life cycle emissions kg-CO2/MWh of each part of a geothermal plant (Soltani et al., 2021).

The global surge in population, economic growth, technological advancements, and improved living standards have significantly increased the demand for energy. Fossil fuels, primarily coal, natural gas, and oil, have been extensively used to meet this growing demand, causing harmful emissions and environmental issues. Many countries, including Türkiye, heavily rely on fossil fuels for energy production, leading to increased carbon emissions and dependence on foreign energy sources. Embracing renewable and sustainable energy sources is vital for both environmental well-being and governments' pursuit of sustainable development. Türkiye stands above the global average in utilizing essential electricity production methods, including solar, wind, geothermal, and hydro energy (Ağbulut et al., 2023).

Türkiye, situated on the Alpine-Himalayan tectonic belt, holds significant geothermal energy potential. The geothermal potential of the country is estimated at 31,500 MWt. It ranks 7th globally and 1st in Europe for geothermal energy, with 78% of potential areas in Western Anatolia, 9 % in Central Anatolia, 7 % in the Marmara Region, 5 % in Eastern Anatolia, and 1% in other regions (Şimşek et al., 2005; Ağbulut et al., 2023). Direct use, geothermal heat pumps, and electricity generation constitute the primary applications of geothermal energy in Türkiye. For electricity generation, the temperature of geothermal sources is crucial. Geothermal areas in Türkiye can be categorized into three groups based on temperature: those with low temperatures (below 90 °C), medium temperatures (90–150 °C), and high temperatures (exceeding 150 °C) (Figure 2). Due to insufficient source temperatures, Türkiye lacks dry steam power plants, but flash steam and binary cycle power plants are prevalent. There are 65 geothermal power plants (GPPs) in Türkiye as of 2022, concentrated in Denizli, Manisa, Aydın, Çanakkale, Afyonkarahisar, and İzmir. Türkiye has become the 4th country globally in terms of installed geothermal power, contributing 3% to the national electricity consumption (Ağbulut et al., 2023; Mertoğlu et al., 2019).

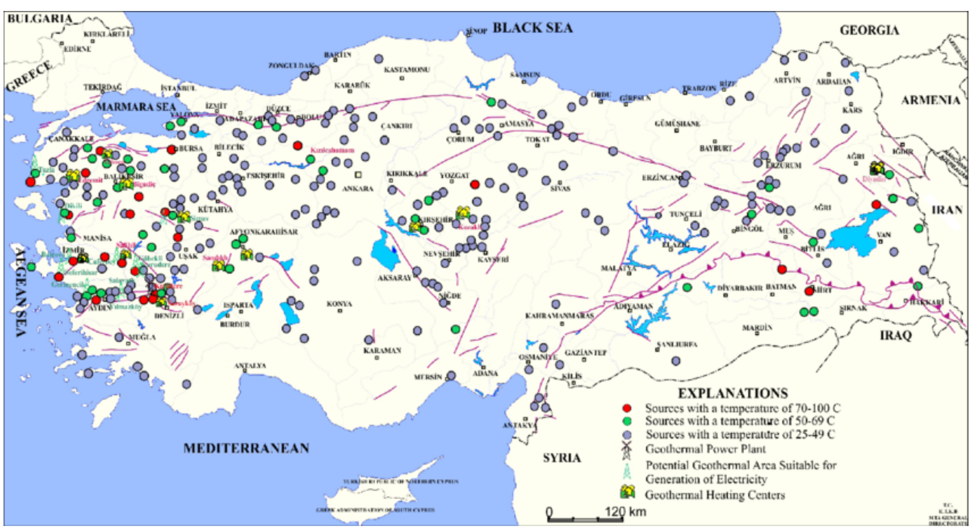

Figure 2. Geothermal Map of Türkiye (MTA, 2022; Görür and Önder, 2022)

This review encompasses a historical survey of the progress in geothermal energy, an examination of geological elements, a recapitulation of previous installations of geothermal power plants, and a discussion on operational challenges. The analysis also explores the policy, legislative, and economic facets of Turkish geothermal power plants. The study concludes by offering insights and future projections for the upcoming generation of geothermal power plants in Türkiye, aiming to provide a thorough understanding of the country's geothermal development history and its impact on economic growth.

2. THE HISTORY OF GEOTHERMAL DEVELOPMENT IN TÜRKIYE

The evolution of geothermal progress in Türkiye, from the initial drilling in 1968 to 2021, demonstrates substantial expansion in the installed power capacity, particularly gaining momentum from 2006 onward. The first geothermal well in Balçova, Izmir, revealed a 125°C geofluid, while a joint project with the United Nations Development Programme (UNDP) in Kızıldere, Denizli, discovered a medium enthalpy reservoir (Serpen and DiPippo, 2022). Despite successful drilling, UNDP's proposed 10 MWe geothermal power plant was not pursued due to the prioritization of large hydroelectric projects. In 1984, a 17.4 MWe power plant was established in Kızıldere. Operational challenges included a significant wellhead pressure drop, requiring the addition of in-fill wells, and severe wellbore scaling, addressed through periodic mechanical cleaning. The plant operated in the 5–10 MWe range until 2000. Initially, no reinjection was employed, and wastewater was discharged into the Büyük Menderes River. In the late 1990s, a deep reinjection well was drilled, and some existing wells were repurposed for reinjection (Serpen and DiPippo, 2022).

Türkiye has made significant strides in geothermal power development, starting with the liberalization of the electrical market in 2000. The Geothermal Energy Code was introduced in 2007, and incentives for geothermal power generation in 2010 further fueled progress. The Renewable Energy Support Scheme feed-in tariff for plants established from 2010 to 2021 was 10.5 US cents per kilowatt-hour, secured for ten years. In 2021, the feed-in tariff was modified to the local currency (lira) and decreased (Richter, 2021).

Geothermal fields refer to areas where heat is transferred. Those with heat flow ranging from 0 to 125.7 mW/m2 are termed regular fields, while those exceeding 125.7 mW/m2 are identified as geothermal fields (Akın et al., 2014). Türkiye possesses significant geothermal potential, with over 170 economically important geothermal fields and 1500 hot, mineralized water sources. Geothermal occurrences are prominent in Western Anatolia, along the North Anatolian Fault Zone, and in volcanic regions in Central and East Anatolia (Şimşek et al., 2005).

Recent progress is centered around using binary plants in areas with moderate temperature resources. Innovative combined flash-binary plants have demonstrated high-efficiency standards in regions with high enthalpy and temperature. Government policies providing incentives for developers and mitigating exploration risks have driven this growth. Commercial development is concentrated in the western part of the country, with potential expansion to the east. By 2020, Türkiye had achieved an impressive 1663 MWe installed power capacity (Figure 3), ranking fourth globally in this category (Mertoglu et al., 2021; Serpen and DiPippo, 2022). The growth in installed capacity and the number of geothermal power units have been exceptional, elevating Türkiye from 10th to second place worldwide in just five years. Türkiye's exponential growth may be challenging to sustain, but ongoing discoveries could solidify its position among global users of geothermal resources for electricity generation.

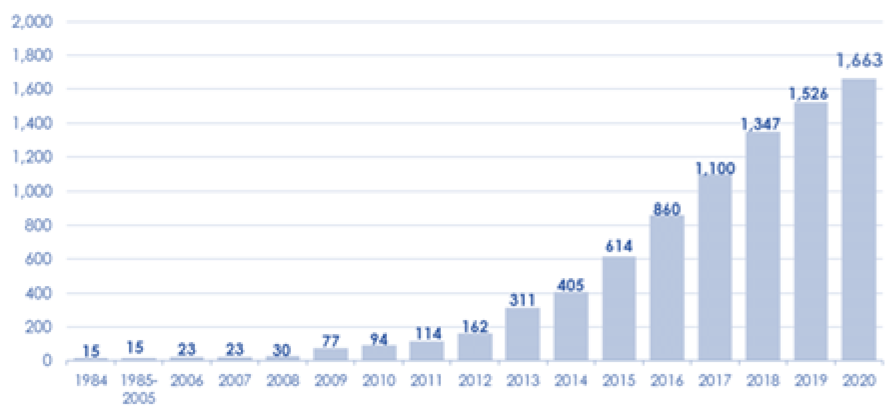

Figure 3. Geothermal Capacity of Türkiye Over the Years (megawatts) (Mertoglu et al., 2021; Serpen and DiPippo, 2022)

3. GEOLOGICAL SETTING OF GEOTHERMAL ENERGY IN TÜRKIYE

Türkiye has significant geothermal energy potential due to its location in a seismically active region characterized by tectonic plate interactions. The country is situated on the complex boundary between the Eurasian, Arabian, and African plates, creating a geologically diverse environment conducive to geothermal activity. Türkiye possesses abundant low-to-moderate enthalpy geothermal resources concentrated in the western Aegean Region, originating from a late north-south extensional regime. Additionally, there are volcanic-related geothermal occurrences in central and eastern Anatolia. Geothermal exploration in Türkiye began in 1948 with a focus on hot springs, and by the early 1960s, efforts intensified (MTA, 2022).

The main geological features contributing to geothermal energy in Türkiye include:

3.1 Tectonic Setting

Türkiye is located in a complex tectonic setting, which makes it favorable for geothermal energy resources (Şimşek et al., 2005). The country is situated at the convergence of several major tectonic plates, including the Eurasian, Arabian, and African. The interaction of these plates results in significant geological activity, creating ideal conditions for geothermal energy development (Gökkaya, 2016; Şimşek et al., 2005) (Figure 4).

North Anatolian Fault (NAF), Hellenic Arc Subduction Zone, and East Anatolian Fault (EAF)—play crucial roles in shaping the tectonic landscape of Türkiye and contribute to the formation of geothermal resources in the region. The NAF is a major transform fault that accommodates the westward motion of the Anatolian Plate. This fault system extends across northern Türkiye and is characterized by right-lateral strike-slip movement (Demirel et al., 2004). The interaction between the Eurasian and Anatolian plates along the NAF creates a complex tectonic environment, forming geothermal reservoirs. The movement along the fault can cause fractures and create pathways for hot fluids from the Earth's interior to reach the surface, forming geothermal systems. Located along the southwestern coast of Türkiye, the Hellenic Arc Subduction Zone involves the subduction of the African Plate beneath the Eurasian Plate. Subduction zones are known for their association with intense geological activity, including volcanic eruptions and seismic events. The subduction of the African Plate generates heat and magma, contributing to volcanic activity in the region. This geodynamic setting also plays a role in the creation of geothermal resources (Görür and Önder, 2002). The heat generated by subduction can lead to the circulation of hot fluids through fractures and faults, forming geothermal reservoirs. The EAF is another significant fault system, located in eastern Türkiye, contributing to the tectonic activity in the region. Similar to the NAF, the movement along the EAF can release heat from the Earth's interior. This release of heat may contribute to the development of geothermal systems in the vicinity of the fault (Uzelli et al., 2021).

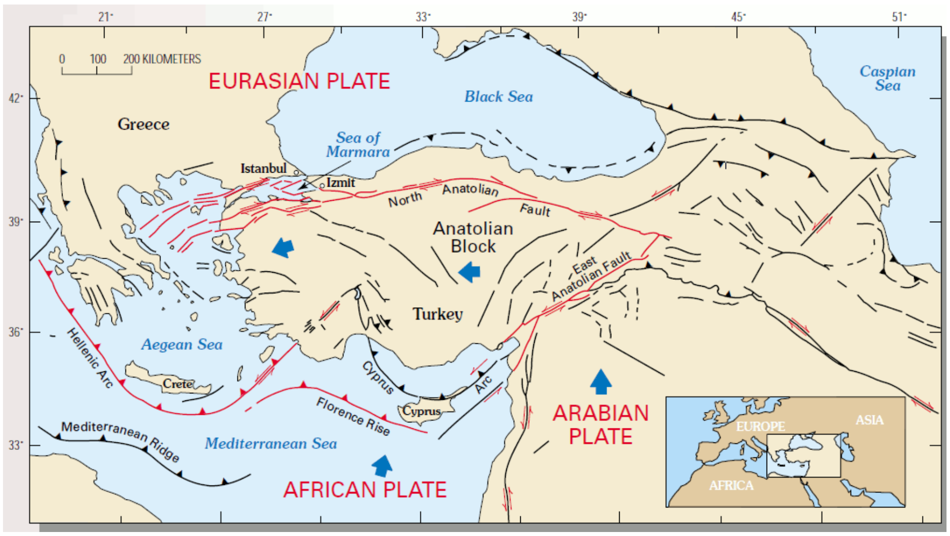

Figure 4. The tectonic map of Türkiye (USGS, 2000; Rockwell et al., 2001; Gökkaya, 2016).

3.2 Volcanic Activity:

Although there are no active volcanoes in mainland Türkiye, the country has experienced volcanic activity throughout its geological history.. Volcanic rocks and tuff deposits in Central Türkiye, including the Cappadocia region, contribute to geothermal resources in this area. As per the conceptual geothermal model of the Cappadocia Geothermal Province, formulated through the analysis of geological, geochemical, and geophysical data, primary and secondary tectonic belts influence the geothermal resources within the area. The reservoir rock in this model is identified as Paleozoic-Mesozoic marble and gneiss. The heat sources are attributed to Late Cretaceous intrusions of granodiorite/gabbro, accompanied by potential heat fluxes reaching the surface due to crustal thinning resulting from regional tectonism. Additionally, the Miocene-Pliocene and Quaternary Cappadocia Volcanics, represented by tuff and ignimbrites, serve as the seal rock for the geothermal system.

3.3 Geological Formations:

The Büyük Menderes Graben (BMG) and the Gediz Graben (GG) represent significant graben systems, hosting geothermal systems with noteworthy medium to high temperatures that are conducive to electricity generation (Figure 5). Examples include geothermal sites like Kızıldere (located in Denizli city), Germencik, Salavatlı, and Pamukören (found in Aydın city) within the BMG, as well as Alaşehir (situated in Manisa city) in the GG. These areas exhibit reservoir temperatures ranging from 170 to 276 °C (Haklıdır and Şengün, 2020).

In western Türkiye, geothermal activity is prevalent, resembling the western Great Basin in the USA. The region is experiencing significant extension, yet relatively little volcanic activity exists. Unlike some areas where geothermal activity is driven by magmatic heat sources, in western Türkiye, it is primarily controlled by faults that facilitate the circulation of hydrothermal fluids. This fluid movement is deep-seated and of meteoric origin. The primary factors influencing geothermal systems in the region include enhanced dilation on east-west-striking normal faults, influenced by various forces such as slab roll-back in the Hellenic subduction zone and the collision of the Arabian plate with Eurasia (Faulds et al., 2009).

While faults play a crucial role in controlling geothermal activity, detailed investigations into the structural controls of individual fields have been limited. The hottest fields, like Germencik and Kizildere, are located near the ends of major standard fault zones, suggesting the presence of multiple splays or horsetails, creating higher fracture density and permeability for fluid flow. Other fields, such as Kurşunlu Canyon and Çamurhamami, occur at dilational fault intersections between major graben-bounding normal faults and oblique-slip, transversely oriented transfer faults. These systems are situated in dilational jogs along transverse faults near the intersection with a significant detachment fault (Faulds et al., 2009).

In the Germencik, Salavatlı, and Pamukören geothermal systems, the primary and deep reservoir, extending along the graben from west to east, exhibits significant fracturing at fault levels within the Menderes Metamorphics. These metamorphic rocks, characterized by high levels of fractures, consist mainly of Paleozoic-aged quartz schist and marbles (Filiz et al., 2000). The Salavatlı geothermal system is situated in the middle of the BMG, while the Pamukören geothermal system lies between Salavatlı and the Kızıldere system. These systems are formed in younger graben deposits adjacent to the metamorphic rocks (Vengosh et al., 2002). In the evolution of the Pamukören system, similar to the Salavatlı and Germencik areas, compressive tectonic activity dominates during the Pre-Miocene phase (Şimşek, 2003). The gneisses are considered effective cap rocks in these geothermal systems.

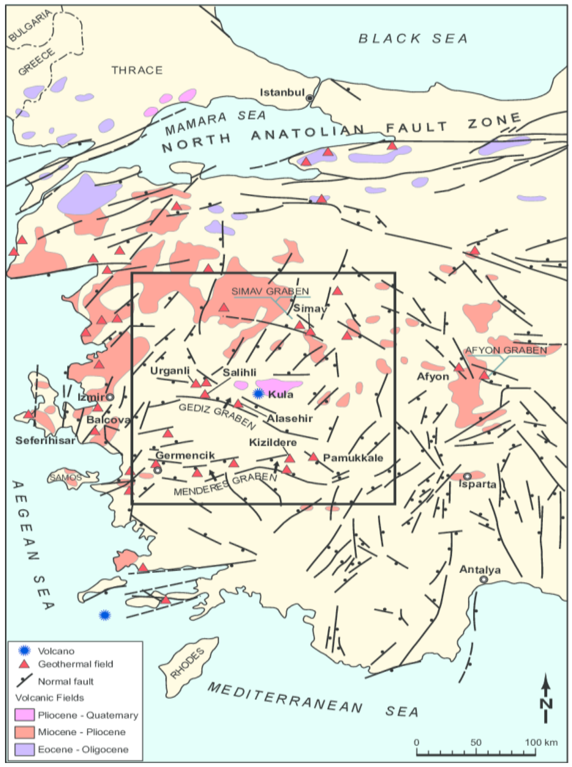

Figure 5. Generalized geologic map of western Türkiye showing locations of geothermal systems (Faulds et al., 2009).

4. GEOTHERMAL ENERGY APPLICATIONS IN TÜRKIYE

Geothermal energy plays a significant role in Türkiye's renewable energy sector, contributing to geothermal heating and approximately 3% of the country's electricity generation. Türkiye is the world's second-largest user of geothermal heating, surpassed only by China (Mertoğlu et al., 2020). The utilization of underground water for heating purposes extends to numerous greenhouses, spas, and residences, with the potential for expanding this method to heat more buildings.

In the late 20th century, Türkiye initiated the generation of electricity from underground steam, and currently, 63 geothermal power plants are operating at 27 geothermal fields as of 2022. Türkiye ranks fourth globally in geothermal power capacity, with an installed capacity of almost 2 gigawatts, positioning it as the fourth-largest in the world. All geothermal plants are concentrated in Western Anatolia due to favorable geological conditions. The potential for geothermal power, including enhanced geothermal systems, is estimated at 5 gigawatts (Richter, 2022).

Despite the potential for electricity generation from hydrothermal sources exceeding the capacity, Türkiye's geothermal sector has substantial direct-use applications, particularly in district heating for over 125,000 households. The direct-use heating extends to various industries, including 4.5 million square meters of heated greenhouses, 520 spas, bathing facilities, and swimming pools (Mertoğlu et al., 2020).

Türkiye's direct-use heating is diverse, serving district heating needs, greenhouse cultivation, and various recreational facilities. Two-thirds of the installed capacity utilizes binary technology, utilizing hot water from the ground to evaporate a fluid with a lower boiling point to drive turbines. The remaining capacity employs the flash cycle, where high-pressure and hot water "flashes" to steam, directly driving turbines. In some instances, competition arises among companies owning wells, impacting the efficiency of geothermal operations (Mertoğlu et al., 2019).

Most of the installed capacity for geothermal power generation is concentrated in the provinces of the Aegean region in western Türkiye. Aydin leads the country with 888 megawatts of installed geothermal energy, primarily comprising licensed power plants (Figure 6) (MENR, 2023)

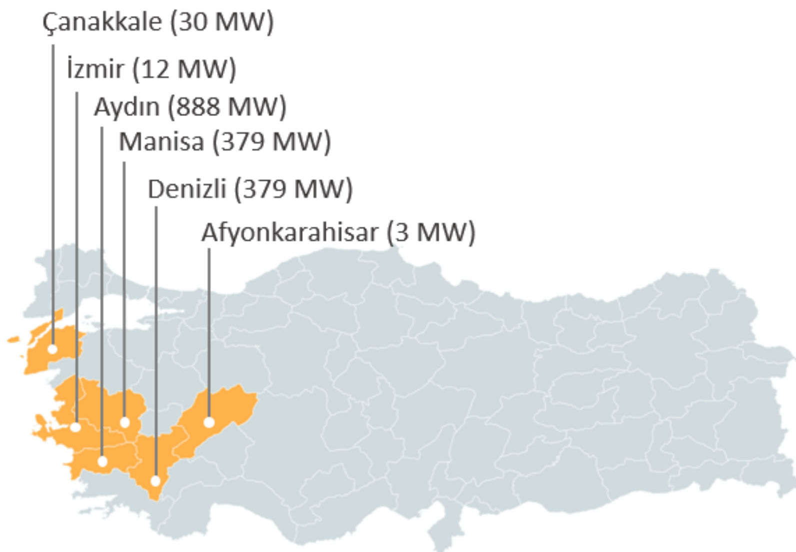

Figure 6. Installed Geothermal Capacity of Major Geothermal Cities of Türkiye (megawatts) (Think GeoEnergy, 2023))

5. OPERATIONAL CHALLENGES AND TECHNICAL ADVANCEMENTS IN GEOTHERMAL FIELDS MANAGEMENT

Successful field management is crucial for the sustainable exploitation of geothermal resources, requiring extensive data from healthy tests, chemical analyses, and production. Conversely, geothermal energy is commonly regarded as an environmentally friendly and renewable power source. However, it may encounter operational difficulties similar to any energy generation approach. The following are some operational concerns linked with geothermal energy:

5.1 Advanced Exploration Techniques

In the geothermal fields of Türkiye, advanced exploration techniques are employed to assess and characterize potential geothermal resources. These methods include geological and geochemical surveys to understand the subsurface composition, seismic studies for imaging subsurface structures, gravity, and magnetic surveys to identify variations in rock properties, and remote sensing for surface feature analysis (Yalcin et al., 2023 & Haklıdır and Güney, 2013; Aslan et al., 2022). Electrical resistivity surveys, exploratory well drilling, and geochemical sampling are utilized to measure subsurface temperature, pressure, and fluid composition directly. Advanced geophysical techniques such as magnetotellurics and electromagnetic surveys provide information on subsurface resistivity (Barbier, 2002). Reservoir modeling and advanced well logging contribute to a comprehensive understanding of the geothermal reservoirs, allowing for optimized reservoir management. The choice of exploration techniques depends on the specific geological characteristics of the region, and ongoing technological advancements may introduce new methods to enhance geothermal exploration in the future.

5.2 Drilling Technologies

Explorations in deep reservoirs are being conducted for electricity generation, involving drilling targets reaching depths of up to 4500m. Successful outcomes include the discovery of deep marble reservoirs, with temperatures around 240°C, in the Kızıldere and Tekkehamam geothermal fields (Şimşek, 2017). Notably, the rise in directional drillings and coil tubing operations represents significant environmental and economic advancements in Türkiye's geothermal fields.

Drilling geothermal wells presents difficulties, including coping with high temperatures, elevated pressures, and challenging lithologies. Special attention is needed to ensure wellbore stability in dispersive shales or pressurized ophiolitic formations, requiring careful planning and execution. Another critical consideration is the minimization of formation damage in the reservoir intervals of geothermal wells. The drilling fluid systems employed in geothermal wells have undergone significant advancements in the past decade. These developments are customized to address challenges not only in the initial and middle sections of the well but also in the reservoir intervals (Mohamed et al., 2021).

Polymers with higher temperature stability and WSMs (Weighted Synthetic Mud) play a crucial role in formulating the mud to attain the drilling fluid characteristics. When the design and implementation are flawless, this fluid system demonstrates its effectiveness in drilling highly challenging formations, addressing sloughing, dispersing, and pack-off potential. Additionally, liquid lubricants may reduce drag while pulling the drilling string through problematic areas (Oner et al., 2020).

5.3 Well Scaling

The deposition of calcium carbonate minerals from geothermal waters occurs through a phenomenon called precipitation, where dissolved calcium and carbonate ions in the water amalgamate to create solid calcium carbonate. This process is influenced by factors such as temperature, pressure, pH, and the concentration of calcium and carbonate ions in the water. In geothermal settings, elevated temperatures often result in heightened mineral solubility. As geothermal waters containing dissolved calcium and carbonate ions reach the surface or encounter cooler conditions, their solubility diminishes, leading to the formation of calcium carbonate minerals. Calcite, aragonite, and vaterite are examples of calcium carbonate minerals that may be generated during this process. These minerals can form deposits, such as travertine terraces found around hot springs, geysers, and other geothermal features (Alper et al., 2015). The specific mineral produced is contingent upon the prevailing conditions during the deposition phase. Diverse forms of calcium carbonate deposits can arise from geothermal waters with varying chemical compositions and temperatures, contributing to the distinctive geological characteristics of geothermal areas. The examination of these deposits can offer valuable insights into the geochemical processes occurring beneath the Earth's surface and facilitate an understanding of the conditions conducive to mineral deposition (Arnorsson, 1989).

High CO_2 levels in Turkish geothermal resources have led to persistent calcite ($CaCO_3$) scaling issues in wellbores, especially during flashing. Initial attempts at solving the problem involved mechanical cleaning, which proved ineffective since the operations continued with periodic mechanical cleaning every six months, causing reduced flow rates and plant shutdowns for scale cleaning. Improved tubing steels and inhibitors introduced in the early 2000s addressed these issues. Inhibitor injection is now a standard procedure in Turkish geothermal fields, whether for flash or binary plants (Haklıdır and Balaban, 2019; Serpen and DiPippo, 2022).

5.4 Corrosion

In Türkiye's significant geothermal fields, the compositions of geothermal fluids generally show low aggressiveness, with total dissolved solid contents ranging from 3500 mg/L to 5000 mg/L. This characteristic is crucial in understanding the potential corrosive effects on the materials used in geothermal energy infrastructure. In certain areas, particularly in the Aegean Coastal Belt, where geofluids are mixed with seawater, the dissolved solid content is notably high (Serpen and DiPippo, 2022). This situation poses a corrosion risk for geofluid gathering pipes. Corrosion can lead to structural integrity issues, affecting the longevity and reliability of the geothermal energy plant (Khasani et al., 2021). To address corrosion challenges, meticulous material selection becomes imperative in regions with higher dissolved solid contents. The materials used for constructing geothermal plants need to withstand the corrosive effects of geofluids mixed with seawater. Proper selection helps ensure the longevity and efficiency of the geothermal infrastructure. Corrosion problems may also arise in geothermal wells, particularly during acid stimulation jobs. Acid stimulation is a well treatment technique used to enhance the permeability of geothermal reservoirs. However, the corrosive nature of the acids employed can pose challenges to the well infrastructure. To mitigate corrosion-related issues, various preventive measures are employed. This includes the use of corrosion inhibitors, which are substances that can reduce the corrosion rate of metals exposed to geothermal fluids. Additionally, aggressive cooling of wellbores is implemented to manage and control the temperature, minimizing the corrosive impact on well components (Serpen and DiPippo, 2022).

5.5 Noncondensable gas (NCG) handling

NCGs in Turkish geothermal resources are composed of 99% (wt.) CO_2. There is a small quantity of hydrogen sulfide, H_2S, in the rest. High carbon dioxide (CO_2) content benefits well productivity but poses issues in condensers and raises environmental concerns. Some geothermal power plants in Türkiye have emitted CO_2 levels comparable to fossil-fuel plants, though such instances are infrequent. Initial NCG emissions decrease over time, affecting well productivity and prompting the use of downhole pumps. Additionally, to combat odor-related problems from hydrogen sulfide (H_2S), the Environment Ministry issued directives with H_2S emission limits, mandating measurement by accredited firms. Facilities must take measures to meet specified levels, adhering to air pollution control regulations for industry compliance. Non-condensable gases can disrupt power generation by diminishing the efficiency of the working fluid in the turbine. To address this issue, effective degassing systems, including flash tanks or alternative separation technologies, are utilized to eliminate non-condensable gases before they reach the turbine. It is essential to monitor gas concentrations diligently to maintain optimal power output (Serpen and DiPippo, 2022; Akkurt and Yildirim, 2008).

5.6 Subsurface Pumping

Downhole pumps are crucial in raising geothermal fluids to the surface, improving overall circulation. These pumps are susceptible to deterioration because of the challenging conditions in geothermal wells. It is vital to consistently monitor pump performance, choose the appropriate pump based on healthy conditions, and conduct regular maintenance, including replacing worn components. This is necessary to guarantee the continuous and efficient operation of the system (Aydin and Sukru, 2021; Aksoy, 2007).

The decline in NCG (non-condensable gas) during geothermal field exploitation has significantly lowered productivity. Efforts to restore production through subsurface pumping and in-fill drilling failed due to sound interference. Türkiye faces challenges in downhole pumping, including high temperature, directional drilling, and low productivity. Two pump types, mechanical line-shaft pumps (LSP) and electrical submersible pumps (ESP), have varying lifespans and effectiveness (Aydin and Sukru, 2021; Serpen and DiPippo, 2022).

Old wells with small casings limit high-capacity pump use, lowering flow rates. Recent wells with larger casings allow for larger pumps and higher flow rates. A closed pumping system has been proposed to mitigate NCG emissions, involving high-pressure pumping of geofluid to the binary plants and reinjection wells. Research projects explore NCG injection via pressurization and re-dissolution, with pilot applications in the planning stages (Serpen and DiPippo, 2022).

5.7 Re-injection

Ensuring a reservoir's long-term viability involves reintroducing used geothermal fluids back into the reservoir. It is imperative to meticulously assess reservoir conditions, such as temperature and pressure, to avoid excessive extraction that may result in reservoir depletion. Strategic placement of injection wells, coupled with continuous monitoring and adjustments to reinjection rates, plays a crucial role in preserving reservoir pressure and thermal equilibrium (Kaya and Zarrouk, 2017; Rivera Diaz, 2016).

In Türkiye, geothermal systems mainly consist of liquid-dominated reservoirs with low-to-medium enthalpy. The global standard involves 100% reinjection in such reservoirs to prevent significant pressure declines. Turkish leaseholders recognize the environmental and reservoir pressure maintenance benefits of reinjection. While early practices were flexible due to low permeability and energy-saving concerns, government oversight has since controlled reinjection operations. High enthalpy resources lose 15-20% of geofluid through flash systems, with the remainder reinjected. Various reinjection strategies are employed considering factors like field size and geology. Deep reinjection is deemed more efficient, and in some cases, reinjection at the production level is preferred. Shallow reinjection may induce downward flow and cool deeper levels. Monitoring microseismic activities and conducting tracer tests assess the cooling impact of reinjection. No subsidence has been observed due to 100% reinjection, attributed to the compact and robust nature of metamorphic rocks (Serpen and DiPippo, 2022; Kaya and Zarrouk, 2017).

6. THE WAY FORWARD AND FUTURE STRATEGIES

The primary focus of the Turkish government's energy policy has consistently revolved around maximizing the utilization of domestic primary energy resources while ensuring a reliable and affordable energy supply for a growing economy in an environmentally sustainable manner. A vital aspect of this policy is the development of 1,000 MW of geothermal electricity generation capacity by 2023, as outlined in the National Renewable Energy Action Plan (Ediger and Akar, 2023). By supporting the private sector in expanding geothermal development, the aims was to establish a mechanism that shares the resource risk linked to geothermal resource validation and facilitates financing for geothermal projects' resource development and construction phases. The Geothermal Development Project (GDP) has been devised to assist the government in creating and implementing these supportive mechanisms (Melikoglu, 2017). The government has established a supportive legal framework to facilitate geothermal development, with the General Directorate of Mineral Research and Exploration of Türkiye (MTA) playing a crucial role in exploration activities.

Despite MTA's pivotal role, it needs more resources and a mandate for extensive geothermal exploration drilling, leading to a slowdown in exploration activities (Dagistan et al., 2015). Private investors holding exploration licenses often need more technical and financial capacity to assume the risks associated with early-stage geothermal exploration. This includes exploration drilling to confirm the presence of geothermal energy sources and validate their commercial viability. Commercial financing for exploration and resource development phases is necessary for many license holders to advance their geothermal prospects

Türkiye possesses considerable untapped geothermal potential, and by leveraging technological progress, implementing supportive policies, and engaging in strategic planning, the nation can enhance the utilization of its geothermal energy resources for sustainable and renewable energy generation. Summarized below are several strategies that can further improve its utilization and sustainability:

- Investing in research to develop more efficient and cost-effective drilling methods can unlock deeper and hotter geothermal reservoirs, thereby expanding the potential resource base.
- Enhancing technologies for improving heat recovery rates from geothermal fluids has the potential to elevate the overall efficiency of geothermal power plants.
- The ongoing exploration and thorough assessment of geothermal resources throughout the country can reveal untapped potential.
- Environmental sustainability requires the implementation of advanced fluid management practices, such as responsibly reinjecting geothermal fluids.
- Mitigating the risk of induced seismicity associated with geothermal operations necessitates investment in sophisticated monitoring techniques.
- Simplifying and streamlining permitting procedures is essential to encourage more rapid and efficient project development.
- Offering financial incentives, subsidies, or tax breaks for geothermal projects can attract increased investment and foster accelerated growth in the sector.
- Upgrading and modernizing the energy grid to accommodate more geothermal power includes integrating balancing technologies for intermittent renewable sources.
- Expanding district heating networks powered by geothermal energy further reduces reliance on fossil fuels for heating purposes.
- Collaborating with international organizations and experts facilitates knowledge transfer and the sharing of best practices, contributing to technology advancement and policy development.
- Encouraging joint research initiatives among academia, industry, and government institutions fosters innovation in geothermal technologies including new patents in the field.
- Increasing public awareness about the benefits and safety of geothermal energy is crucial for gaining public acceptance and support.
- Involving local communities in decision-making processes and ensuring their participation in geothermal projects promotes social acceptance and sustainable development.

7. CONCLUSIONS

In conclusion, the exploration and utilization of geothermal energy in Türkiye have experienced significant growth and development, positioning the country as a prominent player in the global geothermal energy landscape. The rich geological setting, characterized by tectonic plate interactions, faults, and volcanic activity, has endowed Türkiye with substantial geothermal potential, particularly in the western Aegean Region and other volcanic regions in Central and East Anatolia.

Türkiye's commitment to sustainable development and the reduction of carbon emissions has driven the expansion of geothermal power capacity. The government's supportive legal framework and incentives, including the Renewable Energy Support Scheme, have played a crucial role in fostering the growth of geothermal energy. The nation's geothermal capacity has rapidly increased, with Türkiye ranking fourth globally in installed geothermal power capacity, contributing significantly to its electricity generation.

Despite the impressive achievements, the geothermal sector in Türkiye faces operational challenges, including scaling, corrosion, and non-condensable gas handling. These challenges necessitate ongoing technological advancements and innovative solutions to ensure the sustainable exploitation of geothermal resources. Advanced exploration techniques, drilling technologies, and field management strategies are vital for overcoming these challenges and maintaining the long-term viability of geothermal projects.

Looking ahead, Türkiye's future strategies for geothermal energy involve continued investment in research and development to improve drilling methods, enhance heat recovery rates, and explore untapped resources. Environmental sustainability and community engagement are emphasized through responsible fluid management practices, risk mitigation for induced seismicity, and involvement of local communities in decision-making processes.

To further boost the geothermal sector, streamlining permitting procedures, offering financial incentives, upgrading the energy grid, and expanding district heating networks are recommended strategies. International collaboration, knowledge transfer, and public awareness campaigns are also essential for fostering innovation, gaining public acceptance, and achieving sustainable development in the geothermal energy sector.

Türkiye's dedication to maximizing the utilization of its geothermal potential, coupled with strategic planning and continuous technological advancements, positions the country for continued success in the sustainable and renewable energy landscape. Geothermal energy not only contributes to Türkiye's energy security but also aligns with global efforts to combat climate change and transition towards cleaner and more sustainable energy sources.

REFERENCES

Akın, U., Ulugergerli, E. U., and Kutlu, S.: Türkiye jeotermal potansiyelinin ısı akısı hesaplamasıyla değerlendirilmesi. Bulletin of the Mineral Research and Exploration 149, (2014), 205-214.

Akkurt, G. G. and Yildirim, N.: Effect of Non-Condensable Gases on geothermal power plant performance. Case study: Kizildere Geothermal Power Plant-Turkey, International Journal of Exergy, (2008).

Aksoy, N.: Optimization of downhole pump setting depths in liquid-dominated geothermal systems: A case study on the Balcova-Narlidere field, Turkey, Geothermics, 36, 5, (2007), 436-458.

Arnorsson, S.: Deposition of calcium carbonate minerals from geothermal waters- Theoretical considerations. Geothermics 18, (1989), 33–39.

Aslan, G., Aydın, H., and Çakır, Z.: Wide-area ground deformation monitoring in geothermal fields in western Turkey," Turkish Journal of Earth Sciences, 31, (2022).

Aydin, H., and Merey, S.: Design of Electrical Submersible Pump system in geothermal wells: A case study from West Anatolia, Turkey, Energy, 230, (2021).

Ağbulut, Ü., Yıldız, G., Bakır H., Polat F., Biçen Y., Ergün A., and Gürel A. E.: Current practices, potentials, challenges, future opportunities, environmental and economic assumptions for Türkiye's clean and sustainable energy policy: A comprehensive assessment, Sustainable Energy Technologies and Assessments, 56, (2023).

Baba, A., Demir, M. M., Koç, G. A., and Tuğcu, C.: Hydrogeological properties of hyper-saline geothermal brine and application of inhibiting siliceous scale via pH modification, Geothermics, 53, (2015).

Barbier, E.: Geothermal energy technology and current status: an overview, Renewable and Sustainable Energy Reviews, 6, 1–2, (2002), 3-65.

Dagistan, H., Dogdu, N., and Karadaglar, M.: Geothermal explorations and investigations by MTA in Turkey, World Geothermal Congress Melbourne, Australia, 19-25 April 2015, (2015).

Demirel, Z., Yildirim, T., and Burçak M.: Preliminary study on the occurrence of geothermal systems in the tectonic compressional regions: an example from the Derman geothermal field in the Biga Peninsula, Turkey, Journal of Asian Earth Sciences, 22, 5, (2004), 495-501.

DiPippo, R.: Geothermal power plants around the world. A sourcebook on the production of electricity from geothermal energy, draft of Chapter 10 (No. COO-4051-42). Southeastern Massachusetts Univ., North Dartmouth (USA); Brown Univ., Providence, RI (United States), (1979).

DiPippo, R.: Geothermal power plants: principles, applications, case studies and environmental impact. Butterworth-Heinemann, (2012).

Ediger, V. S., and Akar S.: Historical Pattern Analysis of Global Geothermal Power Capacity Development: Preprint. United States: N. p., (2023).

Erge, O., Sakaoglu, K., Sonmez, A., Bagatir, G., Dogan, H. A., Ay, A., and Gucuyener, I. H.: Overview and design principles of drilling fluids systems for geothermal Wells in Turkey, Geothermics, 88, (2020).

Faulds, J., Bouchot, V., Moeck, I., and Oğuz, K.: Structural controls of geothermal systems in western Turkey: A preliminary report. Geotherm Resou Counc Trans, 33, (2009), 375-383.

Filiz, Ş., Tarcan, G., and Gemici, Ü.: Geochemistry of the Germencik geothermal fields, Turkey Proceedings World Geothermal Congress 2000, Japan, May 28- June 10, 2000, (2000), 1115-1120.

Gökkaya, K.: Geographic analysis of earthquake damage in Turkey between 1900 and 2012, Geomatics, (2016).

Görür, N., and Önder, Ş.: Neotectonics of Turkey and its geothermal implication. Bulletin of The Mineral Research and Exploration, (2022).

Gude, V. G.: Geothermal source potential for water desalination–Current status and future perspective. Renewable and Sustainable Energy Reviews, 57, (2016), 1038-1065.

Günther, M., and Hellmann, T.: International environmental agreements for local and global pollution, Journal of Environmental Economics and Management, 81, (2017), 38-58.

Haklıdır, F. S. T., and Balaban T. Ö.: A review of mineral precipitation and practical scale inhibition methods at geothermal power plants in West Anatolia (Turkey), Geothermics, 80, (2019), 103-118.

Haklıdır, F. S. T., and Şengün, R.: Hydrogeochemical similarities and differences between high-temperature geothermal systems with similar geologic settings in the Büyük Menderes and Gediz Grabens of Turkey, Geothermics, 83, (2020).

Haklıdır, F. S. T., and Güney, A.: Geothermal capacity expanding studies in Kızıldere Field. National HVAC Engineering Congress, İzmir, Turkey, April 17–20, (2013).

Hondo, H.: Life cycle GHG emission analysis of power generation systems: Japanese case, Energy, 30(11-12), (2005), 2042-2056.

Jaelani, K., Kusmono, K., Utami, P., and Budiarto, R.: Corrosion in geothermal facilities: Their causes, effects, mitigation, and worldwide cases. AIP Conference Proceedings, (2021).

Johansson, T.B., and Goldemberg, J.: Overview and a policy agenda, Energy for sustainable development, New York: UNDP; (2002).

Kaya, E., and Zarrouk, S. J.: Reinjection of greenhouse gases into geothermal reservoirs, International Journal of Greenhouse Gas Control, 67, (2017), 111-129.

MTA (2022) Geothermal Map. https://www.mta.gov.tr/en/ arastirmalar/jeotermal-enerji-arastirmalari. Accessed in December, 2023.

Mohamed, A., Salehi, S., and Ahmed, R.: Significance and complications of drilling fluid rheology in geothermal drilling: A review. Geothermics, (2021).

Melikoglu, M.: Geothermal energy in Turkey and around the World: A review of the literature and an analysis based on Turkey's Vision 2023 energy targets. Renewable and Sustainable Energy Reviews, 76, (2017), 485-492.

MENR (2023) Ministry of energy and natural resources. https://enerji.gov.tr/tr-tr/sayfalar/jeotermal, Accessed at December 2023.

Mertoglu, O., Şimşek, Ş., and Basarir, N., Paksoy, H.: Geothermal Energy Use, Country Update for Turkey. European Geothermal Congress, Den Haag, The Netherlands, 11-14 June, (2019).

Mertoglu, O., Şimşek, Ş., and Basarir, N.: Geothermal energy use: Projections and country update for Turkey, Proceedings World Geothermal Congress 2020, Reykjavik, Iceland, April 26 - May 2, (2020).

Richter, A.: "ThinkGeoEnergy's Top 10 Geothermal Countries 2021 – installed power generation capacity (MWe)". Archived from the original on 23 January 2022. Retrieved 23 December 2023.

Richter, A.: Turkey introduces updated geothermal energy feed-in-tariff rates, ThinkGeoEnergy. Archived from the original on 25 July 2021. Retrieved 13 December 2023.

Rivera Diaz, A., Kaya, E., Zarrouk, S.J.: Reinjection in geothermal fields − A worldwide review update, Renewable and Sustainable Energy Reviews, Volume 53, (2016).

Rockwell, T., Barka, A., Dawson, T., Akyüz, S., and Thorup, K.: Paleoseismology of the Gazikoy-Saros segment of the North Anatolia fault, Northwestern Turkey: comparison of the historical and paleoseismic records, implications of regional seismic hazard, and models of earthquake recurrence. J Seismol, 5, (2001), 433-448.

Serpen, U., and DiPippo, R.: Turkey - A geothermal success story: A retrospective and prospective assessment, Geothermics, 101, (2022).

Soltani, M., Moradi, K. F., Dehghani-Sanij, A. R., Nokhosteen, A., Ahmadi-Joughi, A., Gharali, K., ... and Dusseault, M. B.: A comprehensive review of geothermal energy evolution and development. International Journal of Green Energy, 16(13), (2019), 971-1009.

Soltani, M., Kashkooli F. M., Souri M., Rafiei B., Jabarifar M., Gharali K., Nathwani J. S.: Environmental, economic, and social impacts of geothermal energy systems, Renewable and Sustainable Energy Reviews, 140, (2021).

Şimşek, Ş., Mertoglu, O., Akkus, N., Ibrahim, B., and Aydogdu O.: Geothermal Energy Utilisation, Development, and Projections– Country Update Report (2000-2004) of Turkey, (2005), 24-29.

Şimsek, Ş.: Hydrogeological and isotopic survey of geothermal fields in the Buyuk Menderes graben, Turkey, Geothermics, 32, 4–6, (2003), 669-678.

Şimşek, Ş., Mertoglu, O., Bakir, N., Akkus I., and Aydogdu, Ö.: Geothermal Energy Utilization Development and Projections - Country Update Report 2000 - 2004 of Turkey Proceedings World Geothermal Congress, Antalya, 24-29 April, (2005).

Think GeoEnergy. "Geothermal Power Capacity in Türkiye Reaches 1691.4 MW." Think GeoEnergy - Geothermal Energy News, June 20, 2023. https://www.thinkgeoenergy.com/geothermal-power-capacity-in-turkiye-reaches-1691-4-mw/.

USGS (2000). Implications for Earthquake Risk Reduction in the United States from the Kocaeli, Turkey, Earthquake of August 17, 1999. U.S. Geological Survey Circular 1193, p. 3. Denver, CO: U.S. Government Printing Office.

Uzelli, T., Şener, M.F., Dölek, İ., Baba, A., Sozbilir, H., and Dirik, R.K.: Structural controls and hydrogeochemical properties of geothermal fields in the Varto Region, east Anatolia, J. Turkish Earth Sci., 30, (2021), 1076–1095.

Vengosh, A., Helvacı, C., and Karamanderesi İ. H.: Geochemical constraints for the origin of thermal waters from western Turkey, Applied Geochemistry, 17, (2002).

Yalcin, M., Sari, F., and Yildiz, A.: Exploration of potential geothermal fields using MAXENT and AHP: A case study of the Büyük Menderes Graben, Geothermics, 114, (2023).