

Review of Geothermal Energy Development in Türkiye: Resources, Technologies, and Future Pathways

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Keywords: Geothermal energy, Türkiye, installed capacity, renewable energy.

ABSTRACT

Türkiye is a leading geothermal power producer in its region while ranking fourth worldwide for geothermal power capacity at 1.73 GW which generated 11.2 TWh of electricity annually during 2024. However, there has been a noticeable slowdown in the rates of increase for both installed capacity and electricity generation during the last few years. The most recent data shows only slight gains in 2025 data, too. The nation has more than 400 geothermal fields in 63 provinces, and it holds geothermal resources in excess of 60,000 MWh, placing the nation as one of the world's largest geothermal energy reserve holders. This study analyzes the Turkish geothermal energy industry by conducting a comprehensive technical assessment of the resource base that underlies the geothermal energy generation systems, direct use applications, and the national strategies to grow the geothermal industry. This study also examines Türkiye's institutional advantage in terms of its established policy framework and its developing domestic supply chain for geothermal-related goods and services while detailing recent challenges and opportunities for geothermal energy to help drive Türkiye's transition to a renewable-energy-based economy.

1. INTRODUCTION

Western Anatolia region of Türkiye (or Turkey) is a prime location for geothermal energy production due to high heat flux from the geotectonic boundary zones connecting the Eurasian, African and Anatolian tectonic plates. The country is ranked fourth globally in terms of geothermal installed power and eleventh globally in terms of total renewable installed power [Cariago, January 2025; EEA, 2025]. Until 2020, both total installed renewable power and installed geothermal power increased rapidly as a result of several factors including favorable geography, favorable climate, a relatively stable economic environment, a young and growing population, and governmental incentives that encouraged increasing investment in renewable energy [Serpen and DiBippo, 2022; Pamukcu et al., 2024]. Policies and purchase guarantees like the Geothermal Energy Code, the Renewable Energy Resources Support Mechanism, and the Renewable Energy Resource Areas had significant contributions to the growth of renewable energy sector including wind, geothermal and solar power [EEA, 2025; Serpen and DiBippo, 2022]. In particular, the feed-in tariff for geothermal plants, which was 10.5 US cents/kWh between 2010 and 2021 (plus some other bonuses), was an attractive rate to encourage investments. However, it was set to Turkish liras in 2021 (with a cap of 8.4 cents/kWh) by tying its effective rate to inflation and exchange rates. Similar rate reductions also applied to other renewable energy sources, but the geothermal industry seems to be affected more by these changes [Richter, 2021].

Geothermal resource research and exploration drilling activities are led by the General Directorate of Mineral Research and Exploration (MRA, or MTA in Turkish). Even though some private investors hold exploration licenses, they may need additional technical capacity, legislative clarity, and financial support/funding opportunities for risky and costly geothermal exploration [Pamukcu et al., 2024]. The monthly and yearly data for installed capacity (in MW), total generation (in MWh) and licensed installed power (in MWe) for renewable and nonrenewable energy sources are periodically released by the Energy Market Regulatory Authority (EMRA) of Republic of Türkiye (which is abbreviated as EPDK in Turkish).

Figure 1 above shows the changes in installed capacity and total generation from 2017 to 2025. Based on the most recent report (December 2025 from EMRA), the electricity generation capacity of Türkiye reached 122.52 GW by the end of December 2025 (from 115.9 GW at the end of 2024) with geothermal power plants contributing 1.43% to the total capacity at 1.76 GW (from 1.73 GW in 2024, respectively). When only licensed installed capacity is considered, the contribution of geothermal plants accounted for 1.78% of the total capacity in 2024 and about 1.77% in 2025. An overwhelming majority of geothermal capacity is installed in Aydın, Denizli and Manisa provinces in Western Türkiye [EMRA, 2025a; 2025b].

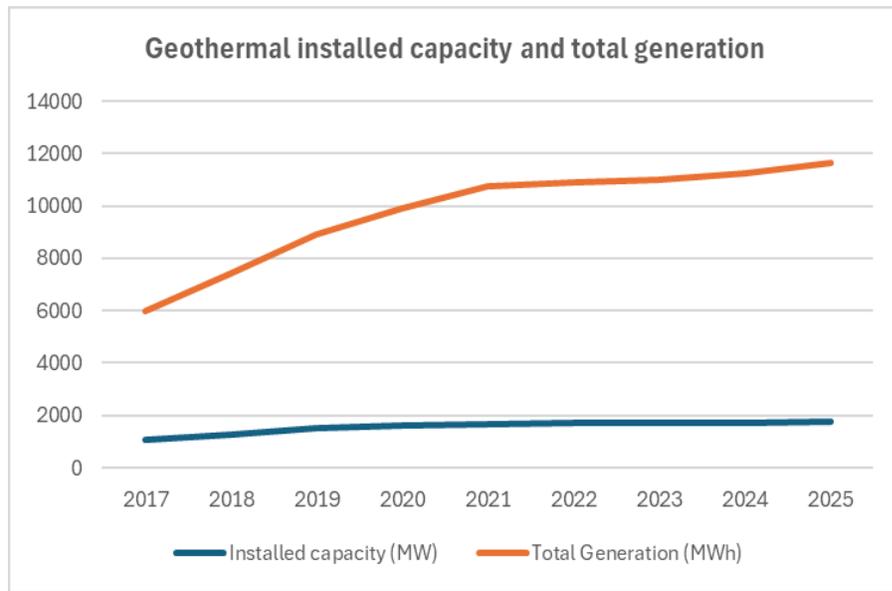


Figure 1. Time series graph of Türkiye’s geothermal installed capacity evolution (in MW) and total generation (in MWh) between 2017 and 2025.

The pie chart below summarizes the individual components of licensed installed capacity at the end of 2024, where about 52.1% of capacity is from renewable sources (Figure 2). When unlicensed categories (mainly solar, natural gas and wind) are also included, the proportion of renewable energy sources increases to 59.4% for the total combined capacity, thanks to the dominating share of unlicensed solar installed capacity (more than 95% among total unlicensed categories).

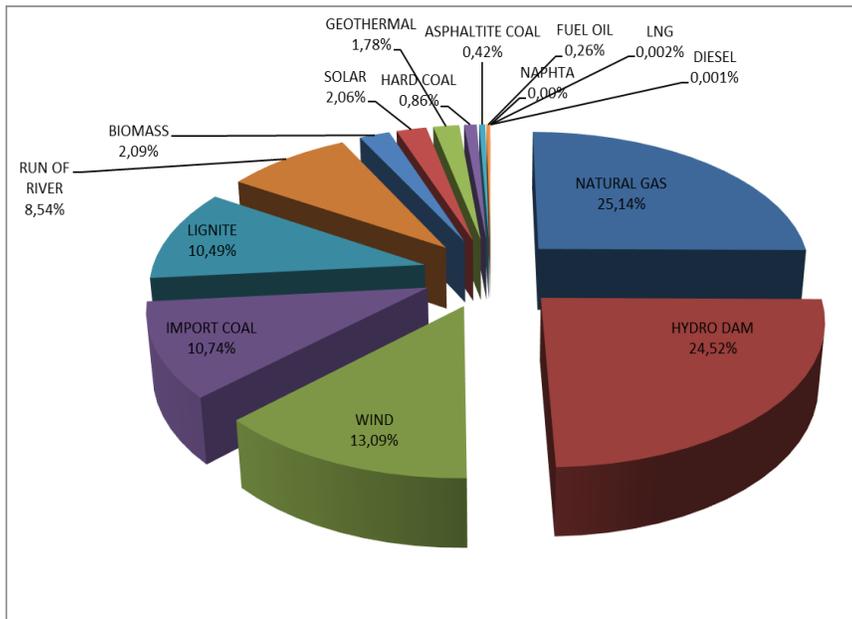


Figure 2. Distribution of licensed installed capacity by sources at the end of 2024. [EMRA, 2025a]

The combined total percentage of renewable sources within installed capacity increased to 62% in December, 2025 (EMRA, 2025b). Their percent distribution is summarized in the bar graph of Figure 3 below:

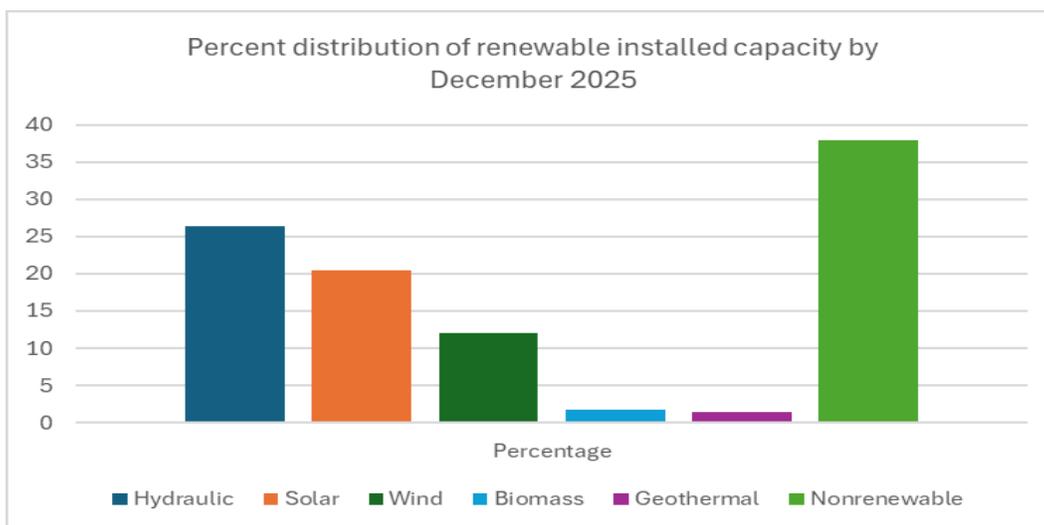


Figure 3. Distribution of total (licensed & unlicensed) installed capacity by renewable sources, December 2025. The graph is depicted based on the data reported in EMRA (2025b) by combining nonrenewable sources together.

The strategic value of geothermal power in Türkiye extends past its role for producing electricity. The country uses its geothermal resources to operate different direct-use systems which include district heating, greenhouse farms, geothermal heat-pump applications, industrial facilities and thermal recreational facilities [Aksoy, 2014; Pamukcu et al., 2024]. Its geothermal power capacity has reached 1966 MWe by December 2025 though this amount was less than national targets [EMRA, 2025b]. Some of the country's benchmarks toward 2030 and 2035 for renewable energy and emissions objectives are close to being on track; however, many of them are a bit below the targets [EEA, 2025]. It is also aimed to add 90 GW renewable power capacity and sustain 65% renewable energy by 2035 through the renewable energy policies to achieve low-carbon energy goals, including harmonization process with the EU, "Sustainable Development" goals (2015), a green deal action plan (2021), ratification of the Paris Agreement (2021) and a national 2053 net-zero emissions target [EEA, 2015].

This review paper investigates four key factors in Türkiye's geothermal industry which include resource distribution patterns, development methods, the status of operational geothermal energy projects as well as the strategies to expand the use of Enhanced Geothermal Systems (EGS) and closed-loop systems.

2. GEOTHERMAL RESOURCE CHARACTERISTICS

The focus of this section is mainly on geological aspects, resource classification and temperature distribution of geothermal resources in Türkiye.

2.1 Geological Setting and Distribution

Türkiye is located within the Alpine–Himalayan orogenic belt, one of the most tectonically active regions globally. Its geothermal potential is primarily controlled by active extensional tectonics, high regional heat flow, crustal thinning, and deep-penetrating fault systems. These geological conditions facilitate deep meteoric water circulation, heating at depth, and subsequent ascent along permeable fault zones [Aksoy, 2014; Pamukcu et al., 2024; Serpen and DiPippo, 2022].

The most significant geothermal province is situated in Western Anatolia, where active crustal extension has developed a series of E–W trending grabens collectively known as the Aegean Graben System. This extensional regime has been active since the Miocene and plays a fundamental role in the formation of high-enthalpy geothermal systems [Aksoy, 2014; Serpen and DiPippo, 2022].

The principal graben systems include the Gediz Graben, the Büyük Menderes Graben, and the Küçük Menderes Graben. These grabens are characterized by:

- Elevated geothermal gradients
- High heat flow (>100 mW/m² locally)
- Intense normal faulting
- Enhanced secondary permeability

Such structural features allow hydrothermal fluids to circulate to depths of several kilometers before returning to the surface along fault-controlled pathways.

Western Anatolia hosts nearly all of Türkiye's high-enthalpy (>200°C) geothermal reservoirs currently utilized for electricity generation. The most prominent example is the Kızıldere Geothermal Field, located within the Büyük Menderes Graben. This field, characterized by

reservoir temperatures exceeding 240°C, produces from fractured metamorphic basement and carbonate formations sealed by low-permeability cap rocks. It was the first geothermal field developed for commercial electricity production in Türkiye and remains one of the country's largest geothermal power producers [Aksoy, 2014; Pamukcu et al, 2024; Serpen and DiBippo, 2022].

Similarly, the Germencik Geothermal Field represents another high-temperature system within the same graben structure, with reservoir temperatures above 230°C. The system is strongly fault-controlled, and production is sustained by fracture permeability within carbonates and metamorphic units. These two fields exemplify the structural and lithological controls that define high-enthalpy geothermal development in Western Anatolia.

Beyond the major electricity-producing systems, numerous medium-enthalpy (90–150°C) geothermal reservoirs are distributed throughout Western Anatolia. In Manisa, geothermal resources associated with the Gediz Graben support both power generation and extensive direct-use applications, including greenhouse heating, agro-industrial processes, district heating, and thermal tourism. The integration of geothermal heat into agricultural activities has contributed significantly to regional economic development.

In İzmir, geothermal systems are widely used for district heating and greenhouse cultivation. The Balçova geothermal district heating network represents one of the earliest urban-scale geothermal heating implementations in the country. Ongoing exploration suggests additional structurally controlled reservoirs suitable for both direct use and potential electricity generation.

Outside Western Anatolia, geothermal systems are more commonly of low to medium enthalpy. In Kayseri and Gaziantep, geothermal resources are associated with regional fault systems, sedimentary basins, and localized volcanic activity. These systems primarily support space heating, greenhouse applications, industrial drying processes, and balneological uses. Eastern Anatolia, influenced by continental collision tectonics between the Arabian and Eurasian plates, exhibits localized high heat flow in volcanic provinces, indicating further potential for future geothermal development.

Nationwide assessments indicate that geothermal resources have been identified in approximately 63 provinces across Türkiye. While high-enthalpy systems suitable for electricity generation are concentrated in Western Anatolia, medium- and low-temperature systems are geographically widespread. Exploration activities rely on integrated geological mapping, geochemical geothermometry, magnetotelluric and resistivity surveys, and exploratory drilling. Despite rapid growth in installed geothermal capacity over the last decade, significant untapped resources remain, particularly for district heating and industrial decarbonization applications.

2.2 Resource Type and Temperature Distribution

The geothermal resources of Türkiye follow this distribution pattern according to [Ağbulut, 2023; Pamukcu et al., 2024; EEA. 2025]:

The majority of geothermal resources in Türkiye fall into the low to medium enthalpy category with temperatures below 150°C which makes them suitable for direct-use applications including district heating, greenhouse agriculture, aquaculture and industrial processing. The medium to high enthalpy geothermal resources primarily exist in Western Anatolia where they can be used for power generation.

Table 1: Major geothermal fields in Türkiye with temperature characteristics and applications

Geothermal Field	Location	Reservoir Temp. (°C)	Primary Application
Kızıldere	Denizli-Aydın	200--242	Power generation, district heating
Germencik	Aydın	216--232	Power generation (dual-flash)
Balçova	İzmir	65--75	District heating
Kayseri	Kayseri	70--90	District heating, greenhouses
Ayvacık	Çanakkale	120--140	Greenhouse, direct use
Salavatlı	Aydın	155--175	Binary power generation

2.3 Case Study: The Kızıldere Geothermal Field

The Kızıldere field with a medium-enthalpy reservoir (in the provinces of Denizli and Aydın) was discovered in 1968, and a pilot power plant with 500kW capacity was constructed in 1974 as Türkiye's initial geothermal plant (the Kızıldere-I flash power plant). It supplied free power to Sarayköy district of Denizli until 1980. In 1984, a 17.4 MWe capacity power plant was commissioned by Turkish Electric Authority [Kaya and Kindap, 2009; Halaçoğlu et al. 2018]. In 2008, Zorlu Group acquired an exploitation license for Kızıldere Geothermal field and Kızıldere-I plant via a privatization tender. Several new wells were drilled including a high enthalpy well (R-1) at a depth of 2261 m with a temperature of 242 °C [Kaya and Kindap, 2009]. Kızıldere-II power plant was added to the field in 2013 with a combined 80MW triple flash-binary arrangement [Aksoy, 2014]. Later, Kızıldere-III power plant with two units was also added to the complex, again with a triple flash-binary system and with an installed capacity of 165 MW, which makes it the leading power plant in Türkiye. Due

to these expansion projects, some wells of Kızıldere-I plant which also showed excessive carbonate scaling issues were taken out of service [Serpen and DiPippo, 2022]. The field contains multiple distinct characteristics that include the following [Aksoy, 2014; Kaya and Kindap, 2009; Halaçoğlu et al. 2018]:

- Operating as a liquid-dominated system with temperatures reaching 200°C at a depth of 500m and 240°C at depths below 1200m
- High horizontal permeability due to intersecting fault networks
- High calcium carbonate scaling in production wells
- Low vertical permeability rates to prevent natural water entry
- Relatively high non-condensable gases (NCG) in the flashed steam (1.7% on average, reaching 3% in R-1 production well)
- Spanning an area of about 100 square kilometers while reaching depths from 370 meters to 2261 meters
- Additional economic and environmental co-products that include dry ice and liquid CO₂ production from high NCG content, local district heating applications, providing geothermal resources for local vegetable greenhouses, and thermal tourism in the region (e.g. by providing free geothermal waters to local hotels and supporting local employment in tourism industry).

The geothermal system shows its resource efficiency because it produces power from various temperature ranges.

3. POWER GENERATION TECHNOLOGIES

This section reviews the principal geothermal power generation technologies employed in Türkiye, with emphasis on flash cycle systems historically and currently implemented in high-enthalpy fields. The selection of power conversion technology in geothermal projects is primarily governed by reservoir temperature, fluid chemistry, non-condensable gas (NCG) content, and economic considerations (DiPippo, 2016).

3.1 Flash Cycle Technology

Flash cycle technology operates by extracting high-pressure geothermal brine from production wells and directing it to a surface separator, where a controlled pressure reduction induces rapid phase change (flashing) from liquid to steam. The separated steam is expanded through a turbine to generate electricity, after which it is condensed. The remaining brine and condensate are reinjected into the reservoir to maintain pressure support and promote sustainable resource management. The efficiency of the flash process is primarily controlled by reservoir temperature, wellhead pressure, fluid chemistry, and non-condensable gas content [DiPippo, 2016].

Single-flash plants, which involve one-stage steam separation, are typically applied to geothermal resources in the 150–180°C range. Türkiye's first geothermal power facility, developed in the Kızıldere field, was constructed using single-flash technology, marking the beginning of commercial geothermal electricity generation in the country. Although thermally less efficient than multi-stage configurations, single-flash systems remain economically attractive for moderate-temperature reservoirs due to their mechanical simplicity and lower capital cost.

For higher-temperature reservoirs exceeding 180°C, dual-flash systems are employed to enhance energy recovery. In this configuration, the residual brine from the first flash stage undergoes a second pressure reduction, producing additional steam that increases overall turbine power output. Modern facilities in the Germencik field utilize advanced dual-flash designs incorporating improved separator systems, optimized turbine staging, and enhanced non-condensable gas extraction technologies [Wallace et al., 2009]. These installations represent the current state-of-the-art in flash steam utilization in Türkiye and contribute substantially to national renewable energy production.

Overall, flash steam technology remains the dominant power conversion method for high-enthalpy geothermal fields in Türkiye, reflecting the structural and thermodynamic characteristics of Western Anatolian reservoirs. Continued technological improvements in turbine efficiency, reinjection strategies, and gas handling systems have further strengthened its economic and operational viability.

3.2 Organic Rankine Cycle

Organic Rankine Cycle (ORC) systems represent the most suitable power conversion technology for Türkiye's medium-enthalpy geothermal resources, particularly those operating within the 100–150°C temperature range [Ağbulut, 2023; Yılmaz, 2020]. Unlike flash steam systems, ORC plants utilize a secondary organic working fluid in a closed-loop configuration, enabling efficient electricity generation from lower-temperature geothermal fluids.

In an ORC system, geothermal brine transfers heat to a low-boiling-point organic working fluid—commonly isopentane, isobutane, or commercial refrigerants—via a heat exchanger. The organic fluid vaporizes and expands through a turbine connected to a generator, producing electricity. The vapor is subsequently condensed and pumped back to the heat exchanger, completing the closed thermodynamic cycle. Since the geothermal fluid and working fluid remain physically separated, the geothermal brine does not enter the turbine, significantly reducing operational challenges associated with scaling and corrosion [DiPippo, 2016].

The advantages of ORC deployment in Türkiye are particularly pronounced in moderate-temperature reservoirs. First, these systems enable economically viable electricity production from resources that would be thermodynamically unsuitable for flash steam technology. Second, ORC plants generate minimal atmospheric emissions because non-condensable gases (NCGs) remain largely dissolved in the reinjected brine. Third, nearly all produced geothermal fluid is reinjected, supporting long-term reservoir pressure maintenance and sustainable field management. Additionally, ORC plants are modular in design, allowing flexible installation of small- to medium-capacity

units aligned with reservoir productivity. Operationally, the indirect heat exchange mechanism reduces the severity of corrosion and mineral scaling, particularly calcium carbonate deposition, which can be problematic in flash systems.

The successful application of binary plant technology under moderate-temperature conditions in Türkiye can be observed at the Salavatlı geothermal field in Aydın Province. The Dora I power plant, recognized as the first private geothermal power investment in the country, was among the earliest facilities to implement chemical inhibitors to mitigate calcium carbonate scaling. Furthermore, the Dora I and Dora II units operated with effective carbon management practices, utilizing separated CO₂ in adjacent dry ice and gaseous CO₂ production facilities (Aksoy, 2014). These developments demonstrate the technical and environmental adaptability of ORC systems within Türkiye’s geothermal portfolio.

Overall, the expansion of binary plant installations reflects the diversification of Türkiye’s geothermal exploitation strategy, enabling efficient utilization of medium-enthalpy resources and enhancing the sustainability profile of the sector.

3.3 Hybrid and Combined Technologies

Most existing Turkish geothermal power plants operate with hybrid systems that utilize flash and binary technology as part of topping and bottoming configurations to improve overall thermodynamic performance. Combined flash-binary power plants outperform single-technology-based systems in terms of efficiency.

Advanced Geothermal Exploration Drilling Technologies:

Drilling in exploration of Turkish geothermal resources involves reaching depths greater than 4500 m to reach hot reservoirs while utilizing drilling and logging tools comparable to those employed in the oil and gas industry [Wallace et al, 2009]. The discovery of deep marble reservoirs at 240°C during deep exploration programs will enable the development of more efficient power generation systems.

Table 2: Comparative technical characteristics of geothermal power generation technologies deployed in Türkiye

Technology	Optimal Temp. (°C)	Efficiency	NCG Emissions
Single-flash	150—180	7--10%	High
Dual-flash	180—250	10--12%	Moderate
Binary (ORC)	100—150	8--12%	Very Low
Flash-binary hybrid	180—240	12--15%	Low

Some examples of geothermal power plants that adopt these technologies include Kızıldere II-III plants as discussed earlier, and Alaşehir-I plant (as a hybrid geothermal and solar plant).

4. CURRENT INSTALLED CAPACITY AND ELECTRICITY GENERATION

In this section, we discuss capacity, generation and geographic distribution of Türkiye’s power plants.

4.1 Fleet Composition and Capacity Distribution

As of December 2025, there are 70 licensed geothermal power plant facilities operating in Türkiye with 1,758 MW of installed capacity. Additionally, installed geothermal electric capacity totaled 1,966 MWe by the end of December, 2025 [EMRA, 2025b]. The Kızıldere Field Complex is the largest geothermal operation in Türkiye.

Annual Electricity Generation:

In 2024, geothermal power plants generated 11.2 TWh of electricity; that was 3.24% of Türkiye's total of 347.2 TWh of electricity generated. In addition, renewable resources represented 45.7% of the country's total energy production in 2024 [EMRA, 2025a]. These percentages were about the same at the end of 2025: geothermal power plants represented 3.23%, while renewable resources accounted for a combined 43.2% of all electricity produced, 360.7 TWh, in Türkiye by the end of 2025 [EMRA, 2025b].

Expansion Pathway:

The rapid expansion of geothermal power generation between 2009 and 2020 benefited from a growing economy, active exploration period in thermal resources and substantial governmental support. However, discovery of economical geothermal reserves in the country seems to be reaching a mature state while most purchasing guarantees and incentives are either diminishing or getting expired [Serpen and DiBippo, 2022]. Moreover, inflation is still quite high and Turkish Lira keeps depreciating with respect to USD. So, new forms of funding and support mechanisms may be needed to encourage the private sector to consider long-term investments in rather risky and costly geothermal explorations and operations.

4.2 Geographic Distribution of Power Plants

As of now, all the operating geothermal power plants are located in Western Anatolia because this area offers the best geothermal resources and existing resource exploration infrastructure. In addition to ongoing exploration activities in Western Anatolia (including Bergama and Menemen areas), new development sites have been identified in Central, Northern and Eastern Anatolia, which could potentially serve as locations for the construction of new geothermal power plants. While geophysical studies are completed in the Giresun-Şebinkarahisar field, geological and geophysical studies are continuing in the licensed fields of Bolu, Düzce, Kayseri and Kırşehir provinces [Cariago, March 2025]. Moreover, there are ongoing exploration and drilling activities in eastern provinces including Diyarbakır and Siirt.

5. DIRECT USE APPLICATIONS

We have briefly provided some examples of direct use applications in earlier sections, e.g. in subsection 2.3. Now, we give additional examples of direct use applications in Türkiye.

5.1 District Heating Systems

Geothermal energy provides affordable thermal power to residential and commercial buildings through direct application in district heating systems. The Balçova district heating system in İzmir operates at 65–75°C geothermal fluid temperatures to provide thermal services to 38,460 households while achieving 76% of its installed capacity utilization [World Bank, 2022].

Environmental and Economic Benefits:

The geothermal district heating system reduces annual CO₂ emissions by 77,106 metric tons when compared to natural gas heating systems. The geothermal district heating system operates at lower costs than all other available energy solutions. The current infrastructure network allows businesses to deliver their services to areas which lack proper access.

Challenges and Expansion Opportunities:

The current geothermal district heating systems are limited to only a few urban areas within the country. The geothermal resources are abundant in some densely populated eastern provinces of Türkiye. So, there is potential and utility to construct thermal infrastructure to serve these areas in the future.

5.2 Agricultural Applications: Greenhouse Heating

There is significant potential for the agricultural sector of Turkey to grow via geothermal direct use applications. Although the Turkish greenhouse industry covers 79,000 ha, only 0.6% of this area utilizes geothermal heating; thus, there exists a large opportunity for expansion [World Bank, 2022].

Geothermally Heated Facilities:

Sultan Greenhouse in Salavatlı (Aydın), utilizes a cascading system to heat space utilizing waste heat produced by a nearby geothermal power plant; the system also utilizes carbon dioxide captured from the same power plant for agricultural purposes.

The government established two Agricultural Organized Industrial Zones (OIZ) in Dikili (İzmir) and Kadıköy (Aydın) to stimulate greenhouse development via geothermal heating systems that function as one unit.

Financial Impacts:

Economic benefits arise from greenhouse operations using geothermal heating systems, with operational costs being reduced by 35%. Therefore, greenhouse growers have the opportunity to increase their area of crop production in regions where there is not enough profit to allow traditional agricultural practices [ICHTP, 2015], while the Turkish Government provides financing for low interest loans to speed up investment in geothermally heated greenhouses through its Ziraat Bank financed program. While Western Anatolia has many geothermal resources and power plants, the eastern provinces of Türkiye provide a vast unexploited development opportunity.

5.3 Thermal Tourism and Balneology

Thermal bath and spa resorts located throughout Türkiye have developed a large network of establishments that utilize geothermal heat to provide hot springs baths for tourist customers coming to Turkey from all over the world. In addition to creating jobs for local residents, these spas create tourism opportunities within the region.

5.4 Aquaculture

Utilizing geothermal energy to generate inexpensive electrical power allows aquaculture farmers to cultivate species dependent on water temperatures including catfish and shrimp, tilapia and tropical fish. Geothermal-based food drying facilities currently operating in Sandıklı (Afyon) and Seferihisar (İzmir) and Karakurt (Kırşehir), illustrate the capability of geothermal energy to support industrial food drying.

5.5 Industrial Applications: Food Processing and Drying

Industrial processes requiring substantial amounts of energy for food processing and dehydration operations will be capable of using geothermal energy to enable the efficient performance of these food processing/drying operations. Successful examples of this type of

operation exist today in geothermal-based food processing/drying facilities that have demonstrated both successful operation and profitability; therefore, these companies can expand into new markets for geothermal-based food processing/drying operations.

The Turkish government is assisting the expansion of geothermal greenhouses through three major programs designed to provide grant money or/and financing assistance to applicants and develop initial system designs.

6. POLICY FRAMEWORK AND FINANCING MECHANISMS

6.1 Policy Framework

Turkish Renewable Energy Law and Feed-in Tariff: The Turkish Renewable Energy Law includes 15-year feed-in tariffs for geothermal power generation, thus providing the long term financial stability necessary to encourage private investors to fund geothermal projects [McBride et al., 2025]. The extended price guarantee represents an important incentive for private investors to invest in geothermal projects.

Turkish Geothermal Resources and Natural Mineral Waters Law: Regulations governing the geothermal industry include regulatory mechanisms for the licensing and resource management of geothermal resources to reduce the time required for permitting geothermal projects.

Commitments to Net-Zero Emissions: The Paris Agreement was made law in Türkiye because it intends to fight climate change by rapidly increasing the number of geothermal power plants in order to utilize more renewable energy sources.

6.2 Mechanisms for Financing and Reducing Risk

World Bank Geothermal Development Program: The World Bank provided \$300 million in loan/grant funds to support the growth of private sector geothermal investment through innovative financing mechanisms [World Bank, 2021].

The Risk Sharing Mechanism (RSM) provides private developers with a means of managing the exploration risk associated with geothermal exploration through a mechanism that apportions excessive drilling costs above a project's budget estimate.

The Loan Facility for Resource Development provides financial aid for developing geothermal reservoirs that have economic constraints. The project was expected to induce private funding of approximately \$555 million for the establishment of over 380 MW of new geothermal power plant capacity.

Supporting Domestic Production Chains: The Turkish government supports the development of domestic geothermal equipment manufacturing by providing subsidies to promote the use of domestically manufactured equipment [McBride et al., 2025]. The initiative generated new job opportunities and improved the overall financial performance of the project through its utilization of locally sourced materials.

6.3 Programs Supporting Direct-Use

Initiatives of the Ministry of Agriculture and Forestry: The Ministry of Agriculture and Forestry supports the development of geothermally heated Agricultural Organized Industrial Zones (OIZ) and provides financial support for special agricultural development projects. Moreover, Ziraat Bank offers subsidized loans for equipment purchases aimed to be used for greenhouse and agricultural facilities.

The government programs demonstrate their commitment to achieve maximum direct-use applications which extend beyond the purpose of generating electricity.

7. CHALLENGES AND TECHNICAL CONSIDERATIONS

7.1 Reservoir Management

Pressure and Temperature Decline: The decrease in reservoir pressure and temperature primarily results from a geothermal reservoir's ineffective operation over time due to the lack of effectiveness of reinjection schemes. The Kızıldere geothermal field, the world's longest-running geothermal field, which has operated continuously since 1974, offers insight into developing successful long-term reservoir management methods by using effective injection schemes [Halaçoğlu et al., 2018].

Non-Condensable Gas Management: The high non-condensable gas (NCG) levels found in Turkish geothermal fields, specifically in Kızıldere (at 1.7%) present numerous operational problems. The NCGs create:

- The corrosive and scaling deposits on equipment, thus making equipment unusable;
- Gases accumulate within turbine casings, thus reducing the turbine performance;
- The opportunity to economically utilize captured CO₂.

Air Emission Handling Systems: The existing regulations provide the framework under which the air emissions system can function adequately.

Scaling and Corrosion: The mineral content in Turkish geothermal fluids forms scales when cooled forming clogs in piping, heat exchangers and turbines. Scaling management research focuses on providing new alternatives to manage scaling in Turkish geothermal facilities currently employing high-cost materials and chemical treatments.

High Initial Costs of Exploring and Developing Hot Dry Rock (HDR) Resources at Depths > 4500 m:

Exploration and development of HDR resources at depths greater than 4500 m require special drilling equipment and personnel, similar to those used in oil and gas exploration and development activities, and therefore result in large capital expenditures for exploratory drilling costs. The Risk Sharing Mechanisms help manage the cost of development through public funding of exploration risk.

8. ECONOMIC IMPACTS AND SUPPLY CHAIN DEVELOPMENT

8.1 Domestic Equipment Manufacturing

Supply chain development of manufacturing and purchasing of geothermal power generation equipment, including supply chain issues associated with geothermal power generation equipment for local markets, was facilitated by the country's renewable energy sector development initiatives.

The Turkish industry developed the capability to produce locally geothermal power generation equipment, such as steam and binary turbines, which meet international performance standards for geothermal applications. Currently, there are no GSHP (Ground Source Heat Pump) systems available in the Turkish market for application to urban heating and cooling. This creates potential opportunities for companies to enter this future market.

8.2 Job Creation and Regional Economic Growth

The development of geothermal power plants in Türkiye has generated significant employment opportunities across multiple sectors of the national and regional economy. Geothermal projects require a multidisciplinary workforce throughout the exploration, development, construction, and operational phases. Employment is created not only in drilling and resource exploration, but also in equipment manufacturing, plant construction, operation and maintenance, and associated technical consulting services.

During the exploration and field development stages, geothermal projects employ drilling crews, geoscientists, reservoir engineers, and field technicians. The expansion of geothermal capacity has stimulated domestic manufacturing and supply chains, including producers and distributors of turbines, separators, heat exchangers, pipelines, pumps, and auxiliary control systems. In addition, geothermal power plants create long-term operational employment for plant operators, mechanical and electrical technicians, and maintenance personnel.

Beyond direct power generation, geothermal development supports indirect economic activity in agriculture and thermal tourism. In Western Anatolia, geothermal heat is widely utilized for greenhouse cultivation, agricultural drying, district heating, and spa facilities. These applications create additional employment opportunities for agricultural producers, service providers, and local enterprises. As a result, geothermal resources have fostered the emergence of specialized employment clusters, particularly in regions associated with the Aegean Graben System.

The cumulative effect of geothermal investments has contributed positively to regional economic diversification, especially in rural areas where alternative industrial activity may be limited. By combining electricity generation with direct-use applications, geothermal energy development enhances local income generation, strengthens industrial linkages, and promotes sustainable regional growth.

9. EMERGING TECHNOLOGIES AND FUTURE PATHWAYS

9.1 Enhanced Geothermal Systems (EGS)

Enhanced Geothermal Systems is a geothermal technology that enables the exploitation of hot dry rock resources without natural permeability. There are four key stages to an EGS system:

- Drilling into the hot dry rock formation at depths of approximately 3 – 5 kilometers.
- Hydraulic fracturing to generate a network of artificially created fractures.
- Heat transfer fluid circulation through the fractured network to extract thermal energy for power generation or direct use.

Potential of EGS in Türkiye:

Türkiye has an abundance of hot dry rock resources located near many of the country's larger urban and industrial zones; therefore, it provides an attractive location for the implementation of EGS. Even though some governmental and industry research studies are conducted for this potential, EGS systems haven't been considered for commercial implementation in Türkiye [Serpen and DiBippo, 2022]. Studies on global cost reductions for EGS predict that EGS costs will drop from \$80/MWh to \$50/MWh by 2035, placing EGS in the same price per megawatt-hour (MWh) cost range as traditional geothermal power [McBride et al., 2025].

Regulatory Environment:

Turkey's central government has indicated its intent to support demonstration project proposals using enhanced geothermal systems, which was demonstrated by exploratory studies indicating the government's intention to adopt innovative geothermal technologies and their favorable regulatory environment in relation to most other countries [McBride et al., 2025].

9.2 Closed-Loop Geothermal Systems

Closed-loop geothermal systems represent an emerging technological approach designed to operate as fully self-contained heat extraction systems. Unlike conventional hydrothermal geothermal systems, which rely on the production and reinjection of naturally occurring reservoir fluids, closed-loop systems circulate a proprietary heat transfer fluid within sealed wellbores and subsurface piping networks. In this configuration, thermal energy is transferred conductively from the surrounding rock formations to the working fluid without direct contact with formation fluids. Consequently, there is no need to extract, handle, or dispose of geothermal brine.

Compared with traditional open-loop geothermal systems, closed-loop technologies offer several technical and environmental advantages. First, they eliminate regulatory complexities associated with geothermal fluid disposal and reinjection management. Second, water consumption is significantly reduced, making the technology attractive in regions where water resources are limited. Third, environmental permitting processes may be simplified, as surface discharge and subsurface fluid reinjection risks are minimized. Furthermore, closed-loop systems are theoretically applicable in a broader range of geological settings, including areas lacking naturally permeable hydrothermal reservoirs, thereby expanding the geographical scope of geothermal exploitation.

Although commercial-scale deployment remains limited globally, closed-loop geothermal concepts are attracting increasing policy and research attention. In Türkiye, preliminary governmental and institutional discussions have begun evaluating the feasibility of implementing closed-loop technologies, particularly in regions where conventional hydrothermal resources are either low-permeability or environmentally constrained. If successfully adapted to local geological conditions, closed-loop systems could complement existing geothermal infrastructure and contribute to the diversification of the national renewable energy portfolio.

9.3 Cascaded and Hybrid Applications

Cascading and hybrid applications utilize geothermal resources to meet the requirements of a variety of end-users, such as electricity production, district heating and greenhouse heating and industrial process heat, thereby increasing the utilization of geothermal resources and improving the financial viability of projects. For example, the Sultan Greenhouse (or Sultan Sera) in Aydın operates as a cascading application because it utilizes waste heat from the power plant to produce greenhouse space heating and agricultural products from the captured CO₂.

9.4 Ground Source Heat Pumps

Ground source heat pumps (GSHP) serve as heating and cooling systems in moderate-temperature climates while using very small amounts of direct geothermal resources. The Turkish market has limited GSHP system adoption which creates opportunities to grow urban heating and cooling solution market in future.

10. STRATEGIC RECOMMENDATIONS AND FUTURE PATHWAYS

10.1 Capacity Expansion to 4,000 MWe Target

To achieve the national target of 4,000 MWe of installed geothermal capacity—originally envisioned for completion by the end of 2030—Türkiye must adopt a coordinated strategy integrating exploration, financing, industrial development, and institutional support. Expanding exploration efforts into underexplored regions of Central and Eastern Anatolia is critical to identifying new high- and medium-enthalpy resources [Melikoglu, 2017; Kaplanoglu, 2020]. While Western Anatolia remains the dominant geothermal province, geological indicators suggest additional potential in extensional and volcanic domains beyond the Aegean Graben System.

Risk mitigation remains a decisive factor in geothermal investment. Continued implementation of risk-sharing mechanisms—such as programs supported by the World Bank—is essential to reduce exploration uncertainty and mobilize private-sector capital. Public co-financing during early-stage exploration should remain a strategic priority, given the inherently high geological risk of geothermal drilling.

Domestic industrial capacity development is equally important. Strengthening local manufacturing of turbines, separators, heat exchangers, pumps, and control systems would reduce project costs, minimize foreign currency exposure, and shorten development timelines. Sustained financial engagement from international development banks and domestic capital markets is also required to establish a stable, long-term financing framework capable of supporting large-scale capacity expansion.

10.2 Expansion of Direct-Use Sector

Beyond electricity generation, the direct-use segment of Türkiye's geothermal sector holds substantial untapped potential, with the capacity to expand operational output by an estimated five- to ten-fold. Policy support aimed at scaling geothermally heated greenhouse cultivation could facilitate the development of more than 10,000 hectares of controlled-environment agricultural production. Such expansion would enhance food security, export competitiveness, and rural economic resilience.

Urban geothermal district heating networks require further integration into new residential developments and community-based heating schemes. Moreover, food processing facilities and light industrial operations should increasingly adopt geothermal heat as a primary energy source to reduce fossil fuel dependency and improve energy cost stability. Market development initiatives promoting ground-source heat pump adoption in urban environments would further diversify geothermal utilization and expand decarbonization pathways within the building sector.

10.3 Integration of New Technologies

The long-term strategic trajectory of Türkiye's geothermal sector must incorporate technological innovation. First, pilot implementation of Enhanced Geothermal Systems (EGS) should be supported to develop domestic expertise in stimulation techniques and reservoir engineering under low-permeability conditions. Such initiatives would broaden the exploitable geothermal resource base beyond conventional hydrothermal reservoirs.

Second, closed-loop geothermal system pilot projects could provide solutions to water management constraints while simplifying environmental permitting processes. These systems may be particularly relevant in geologically suitable but hydrogeologically constrained regions.

Third, hybrid geothermal systems combining flash and binary technologies should be encouraged to maximize thermal efficiency and resource utilization. Finally, advanced reservoir monitoring technologies—including distributed acoustic sensing (DAS) and fiber-optic surveillance systems—should be integrated into operational practice. Real-time subsurface monitoring would enhance reservoir management, optimize reinjection strategies, and improve long-term field sustainability.

10.4 Regional Leadership and Export Opportunities

Türkiye's position as a leading geothermal power producer in its region creates significant opportunities for international expansion. The development of domestic equipment manufacturing capacity provides a foundation for exporting geothermal technologies and engineering services to markets in the Middle East and North Africa (MENA).

In addition, Türkiye can leverage its operational expertise to offer technical advisory and capacity-building services to emerging geothermal markets in East Africa, particularly in countries such as Kenya and Ethiopia, where geothermal resources constitute a major component of national energy strategies. Establishing structured policy frameworks and risk management tools tailored for international project development would further enhance competitiveness in these markets.

By consolidating its manufacturing capabilities, engineering expertise, and financial instruments, Türkiye can strengthen its role as a regional hub for geothermal technology, services, and knowledge transfer.

11. CONCLUSION

Despite recent slowdown in its geothermal expansion and capacity, Türkiye has been a model for sustainable geothermal power development globally because it has combined abundant natural geothermal resources with advanced technologies, adopted forward-thinking policies and offered innovative funding solutions. Türkiye ranks as the world's fourth largest geothermal power producer with approximately 1.8 GW of installed capacity producing more than 11 TW h of power per year from the resources identified to date of greater than 60,000 MW th for expansion.

Türkiye's geothermal sector began with flash cycle systems in the 1970s and transitioned to dual flash and binary and hybrid systems demonstrating the flexibility of the sector in response to changes in the availability of geothermal resources. The geothermal sector demonstrates the resource versatility of the sector through the use of geothermal resources in district heating and greenhouse agriculture and thermal tourism and industrial processing in addition to electricity production.

Renewable Energy Law and the various sector-specific laws and regulations along with new funding options including the World Bank Risk Sharing Mechanism have contributed positively to investment opportunities that attracted both domestic and foreign capital. However, decreases in feed-in-tariff rates, approaching maturity for economically feasible exploration/discovery of geothermal resources in the country, high inflation and other uncertainties affected the government goal to achieve 4,500 MWe of geothermal capacity by 2030. To increase capacity and power generation, it is essential to continue improvements in exploration methodologies, supply chain operations and policy/funding support for the private sector.

The country may continue to maintain its leadership in geothermal development through work on EGS, closed-loop technologies and cascaded-hybrid applications. Other geothermal rich areas have a wealth of experience to draw upon in developing their own low-carbon energy systems and establishing themselves as clean technology leaders in their respective regions.

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