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Sustainable Energy and Turkey: The Role of Geothermal Energy and Energy Planning

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ABSTRACT
This article examines Turkey's geothermal energy potential, current status, and future role, highlighting its vast reserves, particularly in the Aegean Region. Using data from 2018 to 2023, it analyzes the growth of installed capacity and forecasts an annual increase of approximately 100 MW, reaching around 2,500 MW by 2030. Recent advancements in geothermal technologies, especially in energy storage and efficiency, are expected to further enhance Turkey's capacity. The significance of geothermal energy in Turkey's energy planning goes beyond electricity generation, supporting regional heating and greenhouse farming while strengthening energy security and advancing renewable energy targets. The article highlights geothermal energy's role in sustainability, reducing carbon emissions, and supporting local development. In conclusion, the article stresses the need for Turkey to boost geothermal investment, adopt innovative technologies, and implement sustainable strategies. It highlights geothermal energy as a key resource in strengthening Turkey's energy security and achieving sustainable development goals.

Sürdürülebilir Enerji ve Türkiye: Jeotermal Enerji ve Enerji Planlamasının Rolü

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ÖZ
Bu makale, Türkiye'nin jeotermal enerji potansiyelini, mevcut durumunu ve gelecekteki rolünü inceleyerek özellikle Ege Bölgesi'ndeki zengin rezervlerine vurgu yapmaktadır. 2018-2023 verilerini kullanarak kurulu kapasitedeki artışı analiz etmekte ve yıllık yaklaşık 100 MW'lık bir artışla 2030 yılına kadar toplamda 2.500 MW'a ulaşacağını öngörmektedir. Özellikle enerji depolama ve verimlilik alanındaki yeni jeotermal teknolojiler, Türkiye'nin kapasitesini daha da artırması beklenmektedir. Türkiye'nin enerji planlamasında jeotermal enerjinin önemi, yalnızca elektrik üretiminin ötesine geçerek bölgesel ısıtma ve sera tarımına katkıda bulunurken, enerji güvenliğini güçlendirmekte ve yenilenebilir enerji hedeflerine ilerlemeyi desteklemektedir. Makale, jeotermal enerjinin sürdürülebilirlikteki rolünü vurgulayarak karbon emisyonlarını azaltma ve yerel kalkınmayı destekleme etkilerine değinmektedir. Sonuç olarak, Türkiye'nin jeotermal yatırımlarını artırması, yenilikçi teknolojileri benimsemesi ve sürdürülebilir stratejiler uygulaması gerektiği vurgulanmaktadır. Jeotermal enerji, Türkiye'nin enerji güvenliğini güçlendirmede ve sürdürülebilir kalkınma hedeflerine ulaşmada kilit bir kaynak olarak öne çıkmaktadır.

1. INTRODUCTION

Geothermal energy refers to the utilization of heat energy originating from the depths of the Earth's crust. The source of this energy is the water and steam that rise to the surface due to temperature differentials underground. Geothermal energy is a sustainable and environmentally friendly energy source that can be used for direct heating, electricity generation, and industrial processes. This energy source holds significant importance for environmental sustainability due to its renewable nature and ability to minimize carbon emissions [1].

In many countries around the world, geothermal energy is utilized in areas such as electricity generation and local heating. Turkey is rich in geothermal energy potential and is developing various projects to utilize this resource more effectively. Active geothermal fields are particularly concentrated in Turkey's western and southern regions. The Aegean Region, along with provinces such as Nevşehir, Aydın, Manisa, and Denizli, hosts Turkey's leading geothermal energy resources. In these regions, geothermal energy is widely used for both electricity production and greenhouse heating.

Turkey is among the regions worldwide with active geothermal zones and has substantial potential in this field. The current utilization of geothermal energy in Turkey is largely limited to regional heating and electricity generation.

However, when used more effectively, these resources have the capacity to meet a significant portion of Turkey's energy needs [2,3]. The role of geothermal energy in Turkey's energy planning is becoming increasingly important, and its share is expected to grow in the future [4,5].

Beyond electricity production, geothermal energy is effectively utilized in industrial and heating applications. For instance, some geothermal plants in the Aegean Region provide district heating for residential areas and are also used in agricultural activities such as greenhouse heating [6,7]. Additionally, geothermal energy contributes to Turkey's sustainable development goals as an environmentally friendly alternative energy source [8,9].

Although Turkey has made significant progress in the geothermal energy sector, there is a need for technological advancements and increased investments to utilize these resources more efficiently. It is emphasized that geothermal energy should occupy a greater place in energy planning to enable broader utilization [1]. In this context, geothermal energy is anticipated to play an important role in Turkey's future energy portfolio [5,10]

The majority of Turkey's geothermal energy resources are located in the Western Anatolia region, with significant investments made in recent years in the Cappadocia area to enhance geothermal potential. Drilling activities around Hasan Mountain have shown increasing temperature values with depth, and numerical modeling based on these results suggests that the region's geothermal potential is linked to a magma chamber located deeper in the Earth's crust [11].

Geothermal energy in Turkey, particularly in Western and Central Anatolia, is a valuable resource due to its young tectonic and volcanic activity. In 2022, Turkey's geothermal electricity generation capacity reached 1,663 MWe, with total direct heat use at 5,113 MWt. With further research and the development of Enhanced Deep Geothermal Systems (EDGS), Turkey's geothermal capacity is expected to grow significantly, potentially exceeding 100,000 MWt in the medium term [12].

Geothermal energy is a renewable energy source that is highly suitable for Turkey's needs. As primary energy sources are depleting and resources are unevenly distributed globally, local and renewable energy sources are becoming essential for the country. Geothermal energy can contribute to meeting part of Turkey's energy demands, particularly for electricity generation through geothermal power plants [13].

Since 2015, Turkey has made significant advancements in geothermal energy. The country has discovered approximately 460 geothermal fields and reached a geothermal direct-use capacity of 3828.5 MWt for heating, agriculture, and balneological purposes. As of December 2020, Turkey's geothermal electricity production capacity is 1663 MWe, with ongoing deep reservoir explorations and drilling efforts to further enhance electricity production [14].

Turkey is known to have nearly 274 geothermal occurrences, with about 25 fields currently being exploited for direct and indirect energy use. This study evaluates the production data of exploited fields and available data for unexploited fields to estimate the potential of each field in terms of maximum capacity or annual energy use, using geothermal inventory data from MTA and other sources [15].

The Sustainable Development Goals bring together various disciplines such as social, economic, cultural, health, environment, and climate. As the demand for energy increases due to population growth, technological advancements, and rising living standards, the need for clean and sustainable solutions is addressed. In Turkey, significant capacity increases in renewable energy, including solar, wind, biomass, and geothermal, have been achieved, especially with the Renewable Energy Resources Support Mechanism. These developments contribute to energy independence, and Turkey ranks sixth globally and first in Europe in geothermal energy capacity, with diverse geothermal resources across the country used for electricity production, heating, greenhouse farming, and health tourism [16].

This Article includes:

- A comprehensive analysis of Turkey's geothermal energy resources, their current state, potential, and future development trends.
- An evaluation of the role and importance of geothermal energy in Turkey's sustainable energy goals, energy security, and green energy transition.
- Scientific predictions of Turkey's geothermal energy production capacity growth by 2030 (e.g., using linear regression models) and energy strategies based on these forecasts.
- An examination of the potential impacts of investments in the geothermal energy sector on economic growth, local employment, and regional development, as well as opportunities to enhance sector efficiency through innovative technologies.

2. GEOTHERMAL ENERGY IN TURKEY

Turkey's energy planning has been shaped in recent years by a strong focus on sustainable and renewable energy sources. To ensure energy security, reduce dependency on imports, and minimize environmental impacts, Turkey aims to increase the utilization of renewable energy resources. In this context, geothermal energy stands out as a significant alternative energy source due to its potential and environmental advantages [17,18].

The primary objectives of Turkey's energy policies include reducing energy dependency, increasing the use of domestic and renewable resources, and minimizing carbon emissions. As of 2023, Turkey supports geothermal energy through the Renewable Energy Resources Support Mechanism. This mechanism aims to boost geothermal energy investments and increase the share of renewable resources in the country’s energy production [19,20].

While Turkey possesses substantial geothermal energy potential globally, its efficient utilization remains limited. As of 2020, Turkey's geothermal energy capacity was approximately 1,600 MW, with a significant portion allocated to electricity generation. Concentrated primarily in the western regions, Turkey's geothermal resources are centered in provinces like Aydın, Denizli, and Manisa in the Aegean region, which host key geothermal power plants [21].

The critical role of geothermal energy in Turkey’s energy planning lies in its ability to provide both reliable and continuous energy. Unlike other renewable energy sources, geothermal energy can be produced uninterruptedly, which strengthens Turkey’s energy security [5]. Additionally, geothermal energy holds significant potential for local heating and industrial applications, making it an essential resource in meeting the country’s energy needs.

The importance of geothermal energy in Turkey's energy policies extends beyond electricity generation. Geothermal energy also contributes to local development through applications such as regional heating systems and agricultural activities. For instance, geothermal energy is widely used in greenhouse heating, and increased investments in this area have enhanced agricultural productivity in Turkey [6].

Turkey's energy targets for 2023 and beyond foresee an increased share of geothermal energy. In alignment with Turkey's National Renewable Energy Action Plan and Green Deal strategies, the role of geothermal energy in the country's energy production is expected to grow. These targets will play a crucial role in helping Turkey achieve its net-zero emission goals [22].

3. GEOTHERMAL ENERGY SYSTEMS

In order to operate geothermal power plants efficiently and sustainably, it is crucial to accurately model geothermal systems. This modeling process ensures the accurate prediction of subsurface temperature profiles, reservoir properties, fluid dynamics, energy production efficiency, and environmental impacts [23]. One of the key parameters determining the efficiency of geothermal reservoirs is the temperature distribution underground. The subsurface temperature profile is a factor that directly impacts the potential energy production capacity, and therefore, it is necessary to create an accurate temperature map [24]. The porosity and permeability characteristics of the reservoir determine the movement of the fluid and the rate at which heat is transferred to the surface. These properties are important parameters for the sustainable use of geothermal energy; high permeability allows the fluid to move more efficiently [25]. Additionally, the size of the reservoir and fluid dynamics are other critical factors to be considered in the modeling process. The movement of the fluid underground, evaporation rate, pressure changes, and the interaction between liquid and steam can directly affect the efficiency of energy production [26].

To ensure the sustainability of geothermal systems, it is also necessary to model the changes in energy production capacity over time and the recharging processes of the reservoir. Monitoring the changes in temperature and pressure during energy production helps predict the depletion rate of the reservoir and recovery times. These models play a critical role in ensuring the long-term efficiency of geothermal plants [27]. Furthermore, environmental impacts and greenhouse gas emissions are also important parts of the modeling process. While geothermal energy is considered an environmentally friendly option due to its low carbon emissions, the impact of the reservoir on the environment, especially on groundwater and ecosystems, must be accurately simulated [28]. Economic parameters should also be considered in the modeling. The installation costs, maintenance requirements, and energy production costs of geothermal plants are essential for energy planning and resource allocation [29]. Finally, to ensure sustainability in geothermal energy production, the process of reinjecting water into the reservoir, known as "re-injection," must be considered in the models. This process can prevent the reservoir from depleting in the long term and ensure the continuity of energy production capacity.

Accurate and efficient planning of geothermal energy systems will be possible by modeling these critical parameters. This modeling process not only increases energy production efficiency but also minimizes environmental impacts, ensuring the long-term sustainability of the energy plants. The basic principles of geothermal energy are shown in Figure 1 below [30].

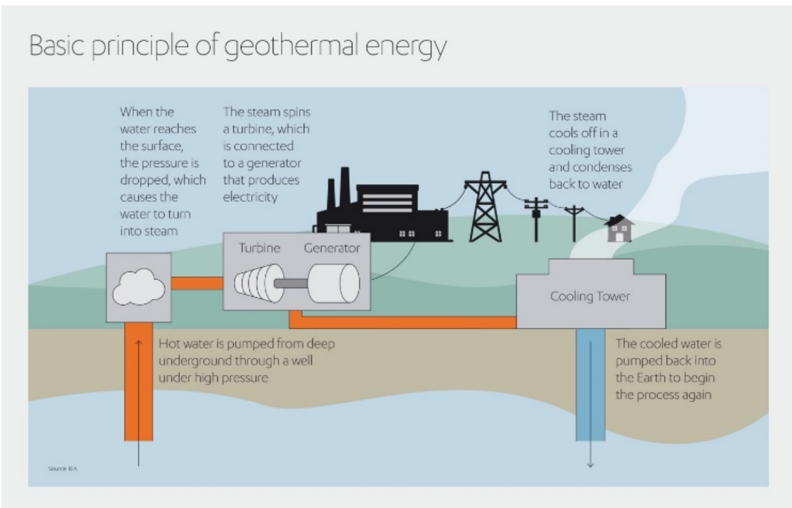

Figure 1. The basic principles of geothermal energy

4. THE ROLE OF GEOTHERMAL ENERGY IN TURKEY'S ENERGY PLANNING STRATEGY

Since the early 2000s, Turkey has taken significant steps towards reducing its dependence on foreign energy sources and increasing the share of renewable energy resources. One of the key components of this strategy is enhancing the potential of renewable energy sources, including geothermal energy.

• Advantages of Geothermal Energy: Geothermal energy is a local and continuous energy source for Turkey. Unlike other renewable energy sources (such as solar and wind), which can be variable depending on seasonal and weather conditions, geothermal energy provides nearly uninterrupted production. Additionally, it significantly contributes to environmental sustainability due to its low carbon emissions.

• Turkey's Geothermal Potential: Turkey is one of the seven largest countries in the world with geothermal energy reserves, and its geothermal resources, concentrated in the Aegean Region, play a crucial role in the country's energy planning. Large geothermal resources in provinces such as Aydın, Denizli, Manisa, and Nevşehir offer a wide range of uses, from electricity generation to heating and greenhouse farming. This situation provides an important advantage for enhancing Turkey's energy security.

4.1. Current Status and Growth Trends

Currently, Turkey's geothermal energy installed capacity is approximately 1,800 MW as of 2023, and it is expected to increase to 2,500 MW by 2030, with an annual growth rate of around 100 MW. These growth trends highlight Turkey's view of geothermal energy as a critical source for reducing energy dependence. This increase in capacity is expected to account for about 3-4% of the country's energy production.

• Share in Electricity Generation: The share of geothermal energy in Turkey's total electricity production is expected to rise to around 3-4%. However, considering its contributions in areas such as district heating and greenhouse farming, the economic impact of geothermal energy on total energy production will be much greater. This demonstrates the need for geothermal energy to play an even larger role in Turkey's energy planning.

4.2. Energy Future and Sustainability

In Turkey's energy planning, the role of geothermal energy is growing in alignment with green energy transformation and sustainable development goals. Geothermal energy significantly contributes to achieving the country's renewable energy targets. Turkey aims to source 30% of its energy production from renewable sources by 2030, and increasing the share of geothermal energy will help Turkey reduce its carbon emissions.

• Capacity Increase and Innovative Technologies: Technological advancements, particularly closed-loop systems and deep geothermal energy, are expected to play a significant role in increasing geothermal's share in Turkey's energy planning. These systems provide more efficient energy production and enhance the efficiency of geothermal plants. Additionally, developments in geothermal heating systems will increase geothermal energy's influence, not only in electricity generation but also in energy efficiency and local heating systems.

4.3. Impact of Geothermal Energy on Energy Security and Local Development

Geothermal energy strengthens Turkey's energy security. Especially energy production based on local resources is critical for reducing import dependency. In regions with significant geothermal potential, local access to energy will increase, contributing to local development.

• Energy Independence: By increasing geothermal energy production, Turkey can reduce its dependency on natural gas and coal imports. Geothermal energy, offering continuous production, provides a more resilient alternative against fluctuations in foreign energy prices. Furthermore, the diversification of Turkey's energy sources will enhance the country's energy security and mitigate the risks posed by international energy market fluctuations.

• Contribution to Local Economy: Geothermal energy plants create local employment during installation and operation stages. Moreover, industries based on geothermal resources, such as greenhouse farming and thermal facilities, can support local development. This creates significant opportunities for social and economic development. In addition, geothermal energy will help reduce unemployment in geothermal-rich regions, stimulate regional businesses, and increase the standard of living for local communities.

4.4. Future Role of Geothermal Energy in Energy Planning and Strategies

Turkey’s goals to increase geothermal energy production will form part of its sustainable energy policy. Steps to enhance the role of geothermal energy in energy planning include:

• Investment Incentives: Turkey should develop policies to attract more investments in the geothermal energy sector. Particularly, support for innovative technologies and domestic production projects should be increased. This includes offering subsidies or tax incentives for companies that implement cutting-edge geothermal technologies and increase local production capabilities.

• Research and Development: Investments in R&D in the geothermal energy field will open the way for more sustainable energy production with efficiency-enhancing technologies. Widespread adoption of innovative methods such as closed-loop systems and high-enthalpy reservoirs is required. Collaborations between universities, private companies, and government institutions will be essential for accelerating R&D and ensuring that new technologies can be quickly brought to market.

• Integrated Energy Strategies: Geothermal energy should not only be used for electricity production but also for regional heating, greenhouse farming, and industrial processes, which would make it much more efficient. Therefore, integrated energy planning targeting multiple sectors should be implemented. This multi-sector approach will reduce the need for fossil fuels in heating, agriculture, and industry, creating a comprehensive renewable energy ecosystem.

Geothermal energy holds an important place in Turkey’s energy strategy, and this role is expected to strengthen by 2030. In addition to its share in electricity generation, geothermal energy will support Turkey’s energy security and sustainable development through its applications in hot water use and local development. Proper management of Turkey’s geothermal energy potential will help achieve domestic and renewable energy goals. With the right investments and policies in place, geothermal energy has the potential to become one of the cornerstones of Turkey’s transition to a more sustainable and energy-independent future.

5. MATERIAL AND METHOD

This section will focus on estimating Turkey's geothermal energy electricity generation capacity until 2030.

Table 1. Turkey's Geothermal Energy Electricity Generation Capacity

Year	Geothermal energy installed capacity (MW)	Annual electricity production (MWh)	Annual capacity factor (%)	Number of geothermal power plants
2018	1,320 MW	5,670,000 MWh	68%	51
2019	1,430 MW	6,110,000 MWh	70%	56
2020	1,515 MW	6,520,000 MWh	72%	60
2021	1,600 MW	6,860,000 MWh	74%	62
2022	1,700 MW	7,120,000 MWh	75%	65
2023 (Estimated)	1,800 MW	7,300,000 MWh	76%	68

Explanations:

- Geothermal Energy Installed Capacity (MW): The total installed capacity of geothermal energy plants in Turkey. This represents the maximum electricity that can be produced by geothermal plants.
- Annual Electricity Production (MWh): The total annual electricity production by geothermal plants. This value is based on the production capacity calculated from the installed capacity.

- Annual Capacity Factor (%): Shows how efficiently an energy plant utilizes its installed capacity. A higher value indicates more efficient operation.
- Number of Geothermal Power Plants: The number of active geothermal energy plants in Turkey.

Methodology:

For this analysis, we selected the linear regression method. Using the historical data on installed capacity (MW) and annual electricity production (MWh) from the past years, we can make predictions for future geothermal energy production. In this model, time (year) will be treated as the independent variable, and the installed capacity or annual production will be the dependent variable. Figure 2 shows the flow chart of the LR algorithm.

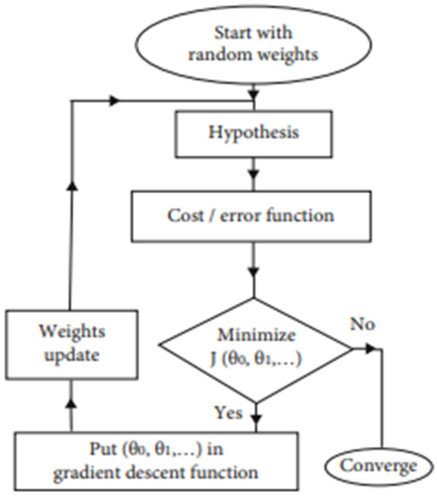

Figure 2. Flow chart of linear regression [31]

The pseudocode of the Linear Regression Alignment Algorithm is as shown in Figure 3.

Preliminaries
combine all n LC/MS runs
build overlapping mass-windows across combined runs
1. Cluster Analysis
for each mass-window **do**
  use p peaks with highest intensities
  calculate distance matrix of pairs of peaks (j, h)

$$d_{j,h} = \begin{cases} \text{diff}(mass), & \text{if } \text{diff}(rt) < k_1 \wedge \text{diff}(\log_{10}(intensity)) < k_2 \\ \infty, & \text{if } \text{diff}(rt) \geq k_1 \vee \text{diff}(\log_{10}(intensity)) \geq k_2 \end{cases}$$

  hierarchical average linkage cluster analysis
  cut cluster-tree at mass accuracy Δ_m
  if $n_{dup} < threshold_1 \wedge n_{miss} < threshold_2$ **then**
    cluster is 'well-behaved'
delete duplicated 'well-behaved' clusters
for each 'well-behaved' cluster **do**
  $\tilde{rt} = median(rt)$
  for each peak i **do**
    $dev_i = rt_i - \tilde{rt}$
2. Regression
for each run s **do**
  take only peaks from 'well-behaved' clusters
  fit regression line $\hat{dev}_{s,i} = a_s + b_s * rt_i$
  by minimizing $\sum (dev_i - \hat{dev}_{s,i})^2$
Correction
for each run s **do**
  for each peak i **do**
    $rt_{cor,i} = rt_i - \hat{dev}_{s,i}$

Figure 3. Pseudocode of linear regression alignment algorithm [32]

Steps:

- Collection and Analysis of Historical Data: First, we will analyze the data from 2018 to 2023.
- Linear Regression Model: We will create a linear regression model for these years. The model will be of the form:

$$Y = a.t + b \quad (1)$$

Where:

- Y is the predicted value (installed capacity or annual production),
- t is the year,
- a is the slope coefficient, and
- b is the constant term.

- Prediction for 2023-2030: Using the model, we will calculate the predictions for 2023 to 2030.

5.1. Historical Data (2018-2023)

We will use the data in Table 2 below to perform the linear regression.

Table 2. Historical data

Year	Installed capacity (MW)	Annual electricity production (MWh)
2018	1,320	5,670,000
2019	1,430	6,110,000
2020	1,515	6,520,000
2021	1,600	6,860,000
2022	1,700	7,120,000
2023	1,800	7,300,000

5.2. Linear Regression Model

The foundation of linear regression is to find the relationship between the year (t) and the installed capacity (Y). The formula is as follows:

$$Y = a.t + b \quad (2)$$

It is assumed that there is a simple linear relationship between year and installed capacity. To find this relationship with the data from 2018 to 2023, we need to compute the slope coefficient (a) and the constant term (b). These calculations are done using the sum of the values.

We can calculate the slope and constant term as follows:

- Slope $(a) = \frac{n\sum(t_i Y_i) - \sum t_i \sum Y_i}{n\sum t_i^2 - (\sum t_i)^2}$ (3)

- Constant Term $(b) = \frac{\sum Y_i - a\sum t_i}{n}$ (4)

Using these formulas, we computed the slope coefficient and constant term based on the 2018-2023 data. The results are:

- Slope $(a) \approx 90.57$ MW/year

This means the installed capacity increases by an average of 90.57 MW per year.

- Constant Term $(b) \approx 1{,}141.6$ MW

This is close to the starting installed capacity in 2018.

5.3. Prediction for 2023-2030

Now, we can make annual predictions for installed capacity from 2023 to 2030 using the slope coefficient we obtained from the model. The formula will be:

$$Y_{2023} = 1{,}800 + 90.57\,.\,(t - 2023) \tag{5}$$

When this formula is applied for the years 2024-2030, the following predicted results are obtained.

Table 3. Predicted installed capacity

Year	Predicted installed capacity (MW)
2024	1,890 MW
2025	1,980 MW
2026	2,070 MW
2027	2,160 MW
2028	2,250 MW
2029	2,340 MW
2030	2,430 MW

5.4. Electricity Production Prediction (MWh)

Electricity production is proportional to installed capacity and determined by the capacity factor. The capacity factor is expected to vary between 75% and 80% over time. To calculate electricity production, we can use the following formula:

Annual Production=Installed Capacity×8,760hours/year×Capacity Factor (6)

Assuming a capacity factor of 76% (0.76) for 2030, we can calculate the predicted electricity production for that year:

- **Predicted Installed Capacity for 2030**: 2,430 MW
- **Capacity Factor:** 76% (0.76)
- **Annual Electricity Production (MWh):** 2,430 × 8,760 × 0.76 ≈ 13,615,000 MWh

The predictions for 2024-2030 are as shown in the table 4 below.

Table 4. The predictions for 2024-2030

Year	Predicted installed capacity (MW)	Predicted annual electricity production (MWh)
2024	1,890 MW	7,515,000 MWh
2025	1,980 MW	7,770,000 MWh
2026	2,070 MW	8,030,000 MWh
2027	2,160 MW	8,290,000 MWh
2028	2,250 MW	8,550,000 MWh
2029	2,340 MW	8,810,000 MWh
2030	2,430 MW	9,070,000 MWh

This prediction shows that Turkey's geothermal energy capacity will continue to grow by approximately 100 MW per year until 2030, and electricity production will increase in parallel with this growth. This model is based on current growth trends and suggests that, with the influence of innovative technologies (e.g., closed-loop systems) and increased investments, higher production capacities may be achievable.

6. CONCLUSION

In conclusion, it is expected that Turkey's geothermal energy potential will continue to play a significant role as an important part of sustainable energy strategies in the future. By 2030, geothermal energy production capacity is projected to reach 2,500 MW with an average annual increase of 100 MW. This growth will not only enhance Turkey's energy security but also contribute to achieving renewable energy targets. Furthermore, beyond electricity generation, the use of geothermal energy in areas such as district heating and greenhouse agriculture will support local development and create economic benefits. Increasing investments in Turkey's geothermal energy resources, integrating innovative technologies, and implementing integrated energy planning will contribute to the country's energy independence, while also significantly supporting environmental sustainability. In this context, it can be said that geothermal energy will occupy an even stronger position in Turkey's energy future and will be an effective tool in achieving sustainable development goals.

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