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Investigation of the Effects of Environmental and Geothermal Resource Temperature on Carnot Efficiency

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Abstract: Geothermal energy is a domestic energy source that is renewable, clean, and environmentally friendly. Türkiye is in a rich position among the world countries regarding geothermal energy due to its geological and geographical location. The vast majority of these resources are located in the western Anatolia region of the country. Today, geothermal energy obtained in the country is used in areas such as electricity generation, heating, thermal and health tourism, industrial mineral extraction, drying, etc. In this study, the potential of a geothermal energy source in Denizli was evaluated using the volumetric method. The effects of time-dependent both ambient and resource temperatures were investigated on an hourly, monthly, and annual basis between 2001 and 2026. The analysis focused on the variation of resource temperature with ambient temperature and the efficiency of the Carnot cycle. The geothermal resource temperature was assumed to be 160°C, with a resource lifespan of 25 years. The lowest source temperature is 100.8°C, and the highest and lowest Carnot efficiencies are obtained as 40.4% and 16.5%. The geothermal resource potential has been calculated to be 74.97 MWe, and the thermal energy stored in the reservoir has been determined to be 5.94×10^{15}J.

Çevre ve Jeotermal Kaynak Sıcaklığının Carnot Verimliliğine Etkilerinin Araştırılması

Anahtar Kelimeler
Enerji,
Yenilenebilir enerji,
Jeotermal enerji,
Hacimsel metot.

Öz: Jeotermal enerji, yenilenebilir, temiz ve çevre dostu yerli bir enerji kaynağıdır. Türkiye, jeolojik ve coğrafi konumu nedeniyle jeotermal enerji açısından dünya ülkeleri arasında zengin bir konumdadır. Bu kaynakların büyük çoğunluğu ülkenin batı Anadolu bölgesinde bulunmaktadır. Günümüzde ülkede elde edilen jeotermal enerji; elektrik üretimi, ısınma, termal ve sağlık turizmi, endüstriyel mineral çıkarımı, kurutma vb. alanlarda kullanılmaktadır. Bu çalışmada, Denizli'deki bir jeotermal enerji kaynağının potansiyeli hacimsel yöntem kullanılarak değerlendirilmiştir. Zamana bağlı hem çevre sıcaklığının hem de kaynak sıcaklığının etkileri 2001-2026 yılları arasında saatlik, aylık ve yıllık bazda incelenmiştir. Analiz, kaynak sıcaklığının ortam sıcaklığına göre değişimine ve Carnot çevriminin verimliliğine odaklanmıştır. Jeotermal kaynak sıcaklığının 160°C olduğu ve kaynak ömrünün 25 yıl olduğu varsayılmıştır. En düşük kaynak sıcaklığı 100.8°C olup en yüksek ve en düşük Carnot verimleri sırasıyla %40.4 ve %16.5 olarak elde edilmiştir. Jeotermal kaynak potansiyeli 74.97 MWe olarak hesaplanmış olup rezervuarda depolanan termal enerji 5.94×10^{15}J olarak belirlenmiştir.

1. INTRODUCTION

Global energy consumption is expanding daily due to population growth, industrialization, and technological advancements. The limited lifespan of fossil fuels and the environmental consequences drive up demand for renewable energy sources [1–5]. Global warming is commonly associated with climate change, increased pollution, and urbanization, as well as the usage of fossil fuels, which primarily contribute to CO_2 emissions [3]. While renewable energy increased historically, fossil fuels still accounted for 82% of total primary energy consumption [6]. Türkiye adopted the United Nations Framework Convention on Climate Change (UNFCCC) in 1992, the Kyoto Protocol in 1997, and the Paris Agreement in 2015, demonstrating its commitment to combating climate change on a global scale. The Paris Agreement marked a paradigm shift in addressing climate change, introducing numerical targets to limit the rise in global temperatures. It was emphasized that to achieve the goal of limiting the global temperature increase to 1.5°C, emissions must be reduced by 45% by 2030, to reach net-zero emissions by mid-century [7]. At the same time, as in many countries, Türkiye also offers various incentives to investors by updating the renewable incentive program called YEKDEM at certain intervals to achieve renewable energy targets [8]. According to the results of the Türkiye National Energy Plan study, electricity consumption is expected to reach 380.2 TWh in 2025, 455.3 TWh in 2030 and 510.5 TWh in 2035. In October 2024, the country's installed power reached 114,599 MW. As of the end of October 2024, the distribution of Türkiye 's installed power by resources is; 28.1% hydropower, 21.5% natural gas, 19.1% coal, 10.9% wind, 16.6% solar, 1.5% geothermal, and 2.4% other resources [9]. It is seen that the share of geothermal energy usage has decreased compared to 2023. This decrease is not related to the decrease in the use of geothermal resources but to the increase in the use of other energy sources. For example, while the share of solar energy was 6.7% in 2023, it reached 16.6% in 2024 [9]. Türkiye ranks 4th among the top 10 countries in the world and first in Europe in electricity production from geothermal resources [1]. However, it is still not able to benefit from this resource at the desired level. For this reason, feasibility studies need to be increased. Geothermal energy was first employed to create electricity in Italy's volcanic regions [10]. In Türkiye, in geothermal energy applications, the first electricity production was started in 1975 with the Kızıldere Power Plant, established by the General Directorate of MTA and having a power of 0.5 MWe [11]. 78% of the areas constituting the country's geothermal potential are located in Western Anatolia, 9% in Central Anatolia, 7% in the Marmara Region, 5% in Eastern Anatolia, and 1% in other regions [11]. Today, geothermal energy obtained in Türkiye is used in heating, thermal and health tourism, industrial mineral extraction, fishing, drying, etc. Geothermal energy production relies heavily on innovative system techniques. These are often referred to as improved geothermal systems. These system techniques include a fuel cell, combined cycle, absorption chiller, cascade system, multi-generation, Organic Rankine Cycle (ORC), Combined Cooling Heating and Power (CCHP), zeotropic, Tri-generation, and Poly-generation. The research provides vital data for investors. The studies show that the first stage is to determine the features of the geothermal resource. The primary reason is that geothermal energy is classed based on its source temperature. There are two distinct systems in the cycle. These systems, which rely on the Rankine cycle principle, are classified as binary and flash-based.

Flash systems use an evaporative heat rejection system at high geothermal source temperatures (above 170 ºC), while binary systems use a heat exchanger at lower temperatures (above 140 ºC). It is commonly used for heating in areas with lower geothermal source temperatures [12]. Geothermal power plants are systems that operate based on ORC. By incorporating solar-hydrogen-carbon capture systems into existing systems, the goal is to increase the gain parameter. Examining the analysis, it is evident that several studies provide hot water, heating, and cooling all year long. Geothermal energy is characterized as a clean, sustainable, steady, and safe energy source [13].

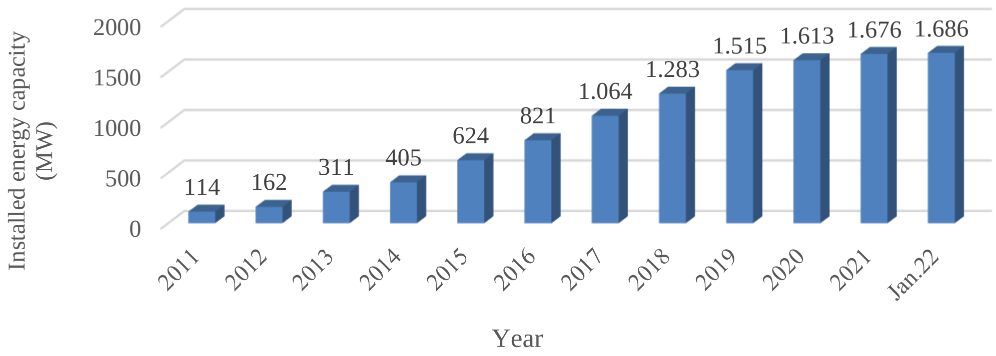
Since geothermal power plants are operated at high capacity, cooling occurs at the source. This cooling spreads over years and negatively affects the efficiency and production of the geothermal power plant over time. The main reason here is that investors try to amortize the cost of the power plant investment as soon as possible and to meet the energy needs of countries first from renewable energy sources. Governments are required to reduce emission rates within a certain period of time in accordance with the Paris climate agreement. Electricity produced from renewable energy sources is prioritized according to the legislations put forward by governments. In other words, priority is given to renewable energy sources in electricity purchases. The biggest disadvantage of renewable energy sources such as wind and sun is that they are not permanent. However, there is no such disadvantage in geothermal energy production. Therefore, the energy produced from geothermal energy sources is continuously fed into the main grid. At the same time, priority is given to the electrical energy produced from these facilities. However, although the use of geothermal resources increases every year, the usage rate remains low compared to the country's geothermal resource potential. The main reason for this is that the resource potential cannot be fully determined due to the inadequacy of technical and economic feasibility studies and the inadequacy of the incentives provided to investors stand out. For this purpose, this study determined a geothermal resource potential for Denizli, the province with the second-highest geothermal energy resources in Türkiye, and examined the impact of ambient and geothermal resource temperatures on the efficiency on an annual, daily, and hourly basis.

2. MATERIAL AND METHOD

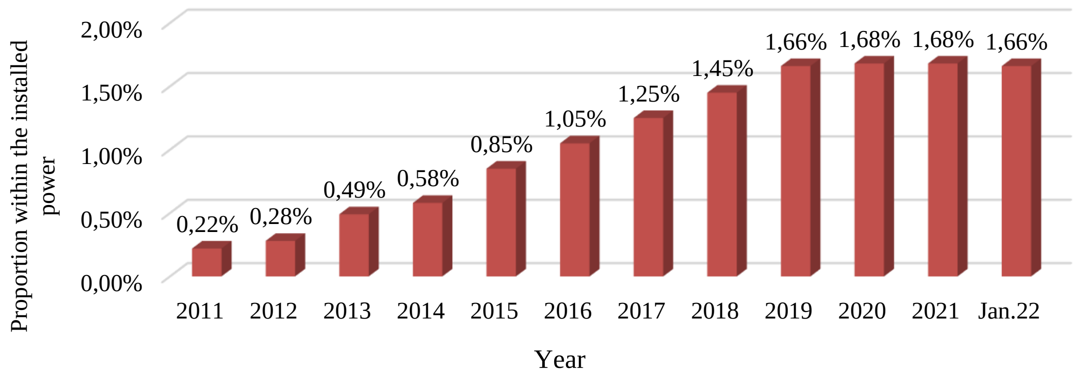
As understood from the literature, Türkiye is in a very good position due to its geological structure in terms of geothermal energy. Although Türkiye is benefiting more from this clean, renewable domestic energy source every year with various supports, it is seen that it uses this energy source less than other energy sources. The top five countries in electricity production from geothermal energy are the USA, Indonesia, Philippines, Türkiye, and New Zealand [9]. The distribution of the country's geothermal energy sources is given in the map in Figure 1.

Figure 1. Türkiye's geothermal energy resources and application map [9]

The areas marked in red on the map represent sources with temperatures ranging between 70–100°C, indicating the highest temperature zones. Green areas correspond to sources with temperatures between 50–69°C, while purple areas indicate temperatures of 20–49°C. The blue areas represent regions with the lowest temperatures. The map demonstrates that the most effective geothermal sources are concentrated in the western part of the country, particularly in the Aegean region [9]. Figure 2(a) illustrates the annual progression of Türkiye's installed geothermal energy capacity (in MW), while Figure 2(b) depicts its proportion within the total installed power capacity (in MW).



a)



b)

Figure 2. Installed power distributions from geothermal energy (MW), Geothermal energy ratio in installed power (%) [9]

From 2011 to June 2022, geothermal energy use has increased steadily every year in both quantity and rate. By the end of June 2022, the installed geothermal energy capacity widely utilized for electricity generation and regional heating reached 1,686 MW, representing 1.66% of the total installed power capacity. However, considering Türkiye's geothermal potential, it is evident that this data is still insufficient.

2.1. Theoretical Calculation

In the study, Türkiye is considered the location. Geothermal energy source temperature values in Türkiye vary between 130 ºC and 232 ºC depending on the area [14]. The location considered in the survey is Denizli (Lat. 37.77 - Lon. 29.1). The volume of the geothermal source whose theoretical analysis was made is up and down 16 km^3 [15]. In the present study, the geothermal source temperature is considered as 160 ºC. Several methods have been employed in the literature to estimate geothermal resource potential, including surface heat flux, planar fracture analysis, magmatic heat budget, total well flow, volumetric estimation, mass-in-place evaluation, and power density assessment [16]. In this study, the geothermal resource potential was determined using the volumetric method. The calculations were conducted by Equation 1 [16].

$$MWe = \frac{Q_{geo} \times R_f \times \eta_{conv}}{L \times F} \tag{1}$$

F in Equation 1 indicates the power plant capacity factor (%90). R_f represents the recovery factor (%15). L represents the power plant life. In this study, L is considered as 25 years. The Q_{geo} (J) value in Equation 1 represents the thermal energy stored in the reservoir. It was calculated using Equation 2 [16].

$$Q_{geo} = \rho_r c_r V(T_i - T_\infty) \tag{2}$$

Here, volumetric heat capacity of the reservoir rock ρ_r = 2550 kg/m^3 - c_r = 1000 J/kgK is expressed [17]. V is the volume of productive reservoir (m^3). Volume of productive reservoir is an important parameter. A small volume reservoir directly affects the working life of the geothermal power plant [17]. In the current study, the V value is considered as 16 km^3 [17]. T_i and T_∞ values are the initial temperature of lithology and environmental temperature (ºC), respectively. The environmental temperature value is taken from NASA POWER WEB (2024) [18]. The received data covers the years from 2001 to 2026 depending on the location. The received data is hourly environmental temperature value (NASA POWER WEB, 2024). The source from which the data is taken shares only 20 years of hourly data. Therefore, the values considered in the analyzes are the same between the values between 2016-2021 and 2022-2026. The data source used for location-dependent ambient temperature was chosen because it has been used reliably in many articles [4,8]. In this application that NASA has made available to users, many meteorological data can be obtained hourly, daily and annually depending on the specified location. To calculate the geothermal resource temperature at the end of 25 years, the energy loss in the resource was calculated with Equation 3.

$$Q_{geoloss} = Q_{geo} \cdot (1 - e^{-\lambda t}) \tag{3}$$

In Equation 3, λ and t values in the third equation indicate the loss coefficient and hourly time, respectively. The λ value takes values between 0.02 and 0.5 [19] annually in the analyses in the literature. However, these figures may change based on the geothermal resource's properties. In this study, the hourly λ value has been taken as 2.282x10^{-6}. After the losses in the geothermal resource depending on the environmental temperature on an hourly basis, the final temperature value of the geothermal resource was calculated with Equation (4), (5).

$$Q_{geofinal} = Q_{geo} - Q_{geoloss} \tag{4}$$

$$T_{geofinal} = \frac{Q_{geofinal}}{\rho_r \cdot c_r \cdot V} + T_\infty \tag{5}$$

The T_{geo} value in Equation 5 represents the hourly final temperature value of the geothermal source. η_{conv} is conversion efficiency. This value is determined in the literature using two alternative approaches, based on the geothermal source temperature or reservoir enthalpy value [20]. In this study, a method based on enthalpy (710 kJ/kg) is adopted. conversion efficiency is calculated via using Equation 6 [20].

$$\eta_{conv} = 6.6869 \ln(h) - 37.930 \tag{6}$$

It should be noted that Equation 3 is appropriate for binary plants. Researchers choose these strategies based on their input parameters. The Carnot efficiency of the plant is calculated with Equation 7.

$$\eta_{carnot} = 1 - \frac{T_c}{T_h} \tag{7}$$

Here, η_{carnot} is Carnot efficiency (%), T_h is the temperature of the heat source (K), and T_c is the temperature of the ambient (K).

3. RESULTS

Denizli province is one of Türkiye's leading regions in renewable energy production due to its abundant geothermal resources and significant investments. According to data from NASA POWER WEB, the average temperature in the region between 1997 and 2022 is 14.55 ºC, while the average wind speed is 2.8 m/s [16,18]. As geothermal energy serves as the primary energy source in the area, accurately identifying and assessing the potential of this resource is of great importance. In the study, the first step involves determining the geothermal resource potential. In this context, the geothermal resource potential has been calculated as 74.97 MWe using Equation 1. It has been observed that numerous analyses on this topic have been conducted in the literature. The geothermal resource potential is reported to vary between 4 and 100 MWe**,** depending on the parameters considered [16]. The thermal energy stored in the reservoir was calculated using Equation 2 and determined to be 5.94 x 10^{15} J. In the literature, for source temperatures between 150–250°C and a depth of 3 km, the heat content value is reported to range between 5.1×10^9 J [21] and 5×10^{22} J [22]**.**

The geothermal resource temperature was calculated hourly over a period of 25 years, providing insight into the long-term thermal behavior of the reservoir. These findings contribute to a better understanding and evaluation of geothermal energy potential and allow for comparisons with other studies in the literature. If additional details or analysis are required, further support can be provided.

The hourly change in a geothermal source in a day is presented in Figure 3. It is seen from the figure (Figure 3) that the change in the ambient temperature does not change significantly. The axis on the right of the graphs shows the Carnot efficiency (ƞ). Since the ambient temperature is generally high between 8:00 a.m. and 6:00 p.m., it has been observed that the Carnot efficiency increases inversely during this time period. While the efficiency reached a maximum of 35.6 % in 2002**,** it was observed to decrease to 25.8 % by January 2026**.**

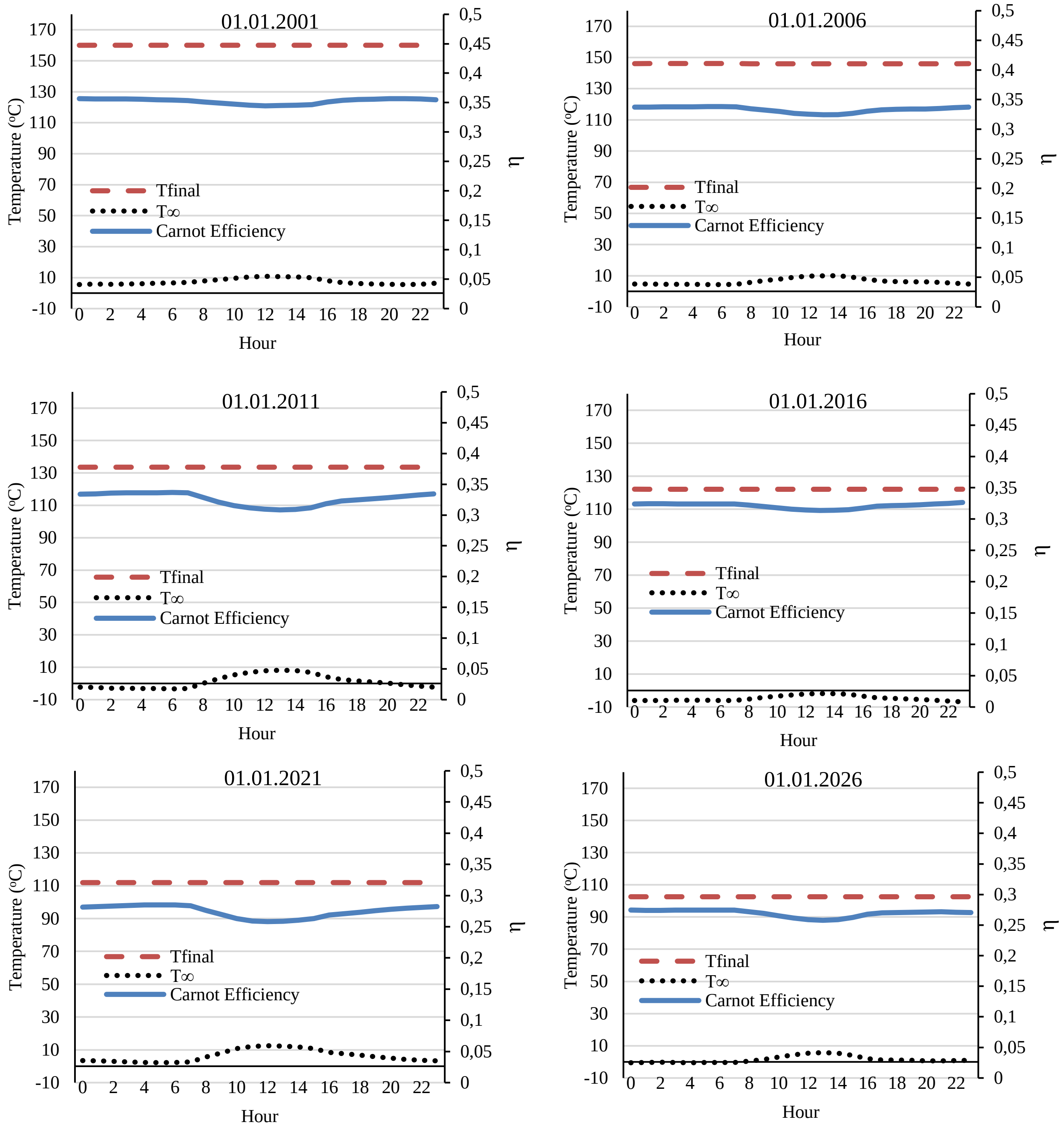


Figure 3. Hourly change in a geothermal resource in a day

The direct effect of the hourly decrease in ambient temperature on the geothermal resource potential for the years 2001-2026 is clearly seen. The initial source temperature of 160°C decreased over time, reaching 146.0 °C in 2006, 133.5 °C in 2011, 122.1°C in 2016, and 111.8 °C in 2021, 102.6 °C in 2026 depending on the ambient temperature (As of January 1st). The Carnot efficiency in these years is 35.6 % - 34.4 % in 2001, 33.8 %- 32.4 % in 2006, 33.3 %-30.8 % in 2011, 32.6 % - 31.3% in 2016, 28.4 % -25.8 % in 2021 and 27.3 % - 25.8 % in 2026. The ambient temperature is 5.5-10.8 °C in 2001, 4.3-10.2 °C in 2006, -3.3 °C - 8.1 °C in 2011, -6.9 °C to -1.8 °C in

2016, 2.1 °C -12.2 °C in 2021 and -0.5 °C -5.7 °C in 2026 (January, 01).

There is a clear inverse relationship between Carnot efficiency and ambient temperature, as lower ambient temperatures generally correspond to higher efficiency values. This correlation aligns with the theoretical principles of Carnot efficiency, which improves as the temperature difference between the heat source and the ambient increases. Over the years, fluctuations in ambient temperature appear to have influenced efficiency levels, with the trend toward decreasing efficiency in recent years partially attributable to rising minimum ambient temperatures and reduced temperature differentials.

The hourly change in geothermal resources for a month is given in Figure 4.

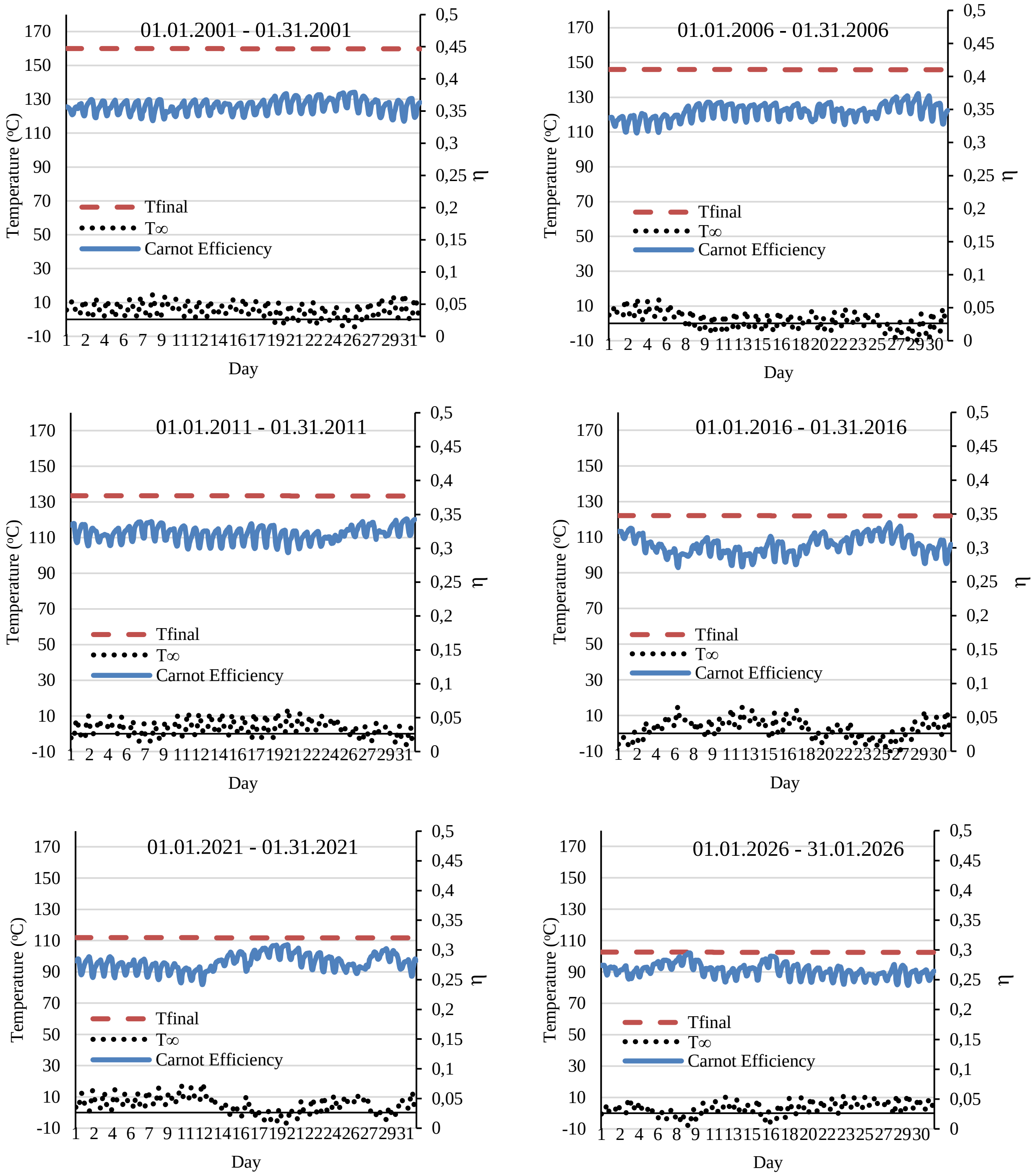


Figure 4. Hourly change in a month's geothermal resource

The change in geothermal resource potential over one month (January 1–31) is presented in Figure 4, covering the years 2001–2026. While no significant variability is observed in geothermal resource temperature, notable fluctuations are evident in geothermal resource potential values. These fluctuations appear to have a cumulative effect over time, as illustrated in Figure 4. Additionally, the ambient temperature during this period ranges from -4.4 °C to 15.1 ºC. The variability in ambient temperature has a pronounced impact on the geothermal resource potential. During the specified period, the geothermal resource potential fluctuates between 160 ºC and 102.4ºC. The geothermal resource temperatures reached at the end of each month at 5-year intervals from 2001 to 2026 are 159.7 ºC, 145.8 ºC, 133.3 ºC, 121.9 ºC, 111.7 ºC and 102.4 ºC, respectively. Depending on the geothermal resource and ambient temperature, minimum and maximum Carnot efficiency varied between 33.4-37.6% in 2001, 31.4-37.2% in 2006, 29.3-34.2% in 2011, 27.1-33.6% in 2016, 24.1-30.8% in 2021 and 24.0-29.4% in 2026. As expected, there were decreases in Carnot efficiency depending on the increasing ambient temperature at the end of each year.

In Figure 5, it shows the hourly change in the geothermal resource according to years.

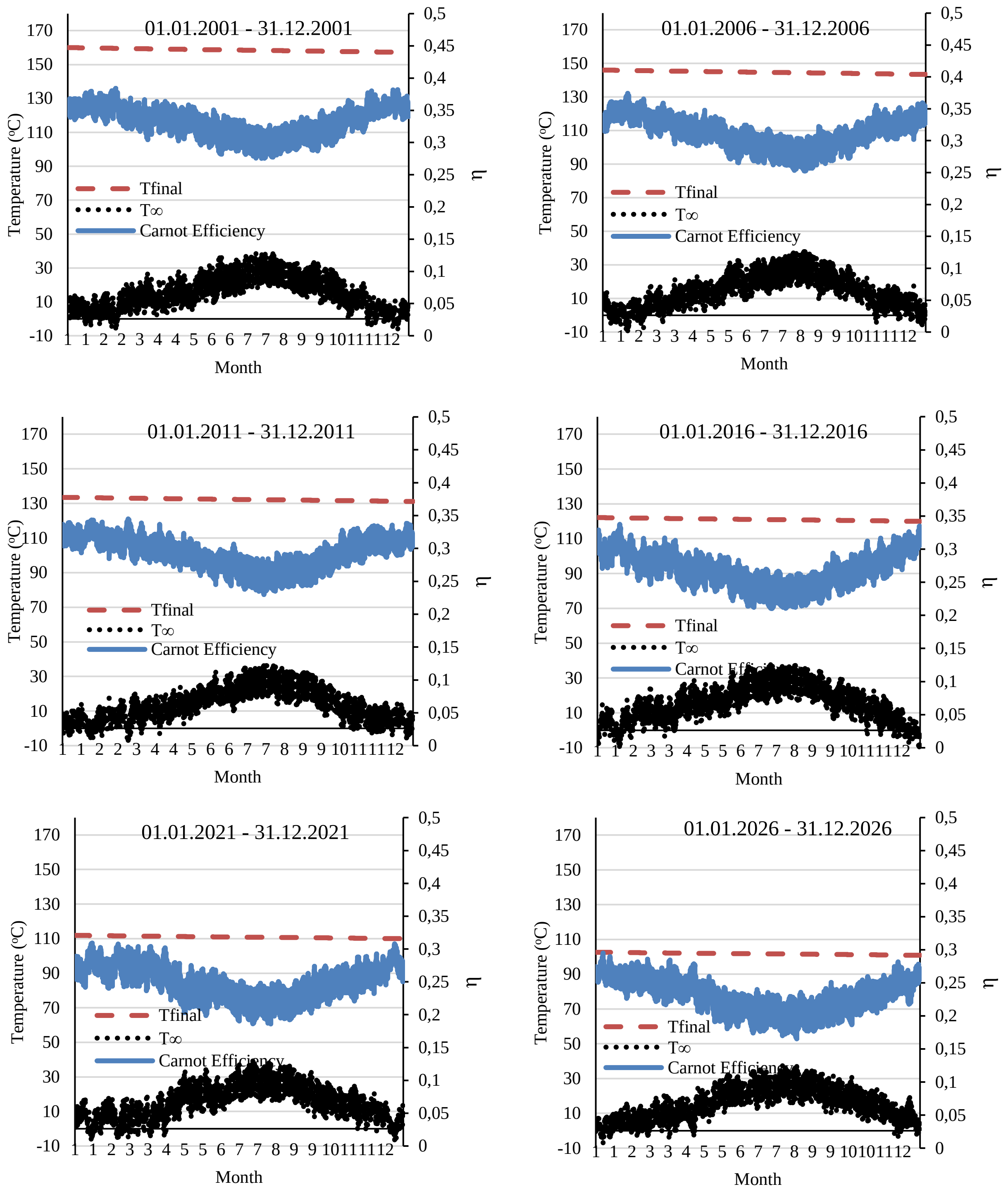


Figure 5. Hourly change in the geothermal resource according to years

As can be seen from the graphs here (Fig.5), the examination was carried out for each year (January 1 - December 31) at five-year intervals (2001-2026). The results were generated using daily data. During this period, the geothermal resource temperature values decreased to 157.1 ºC at the end of 2001, 143.5 ºC at the end of 2006, 131.1 ºC at the end of 2011, 120.0 ºC at the end of 2016, 109.9 ºC at the end of 2021 and 100.8 ºC at the end of 2026. The decrease difference for each five years was calculated as 13.6 ºC, 12.4 ºC, 11.1 ºC, 10.1 ºC and 9.1ºC, respectively. As can be seen from these data, the difference has tended to decrease over the years. Figure 5 more clearly illustrates the inverse relationship between Carnot efficiency and ambient conditions. The Carnot efficiencies calculated for every five years under examination are as follows: 27.5%-38.1%, 25.7%-37.0%, 23.6%-34.1%, 21.6%-33.2%, 18.5%-30.3%, and 16.5%-29.3%, respectively. This trend highlights the progressive decline in Carnot efficiency over the years, further emphasizing the impact of environmental factors on thermodynamic performance.

Figure 6 shows the change in Carnot efficiency and temperature of the geothermal resource depending on the ambient temperature between 2001-2026.

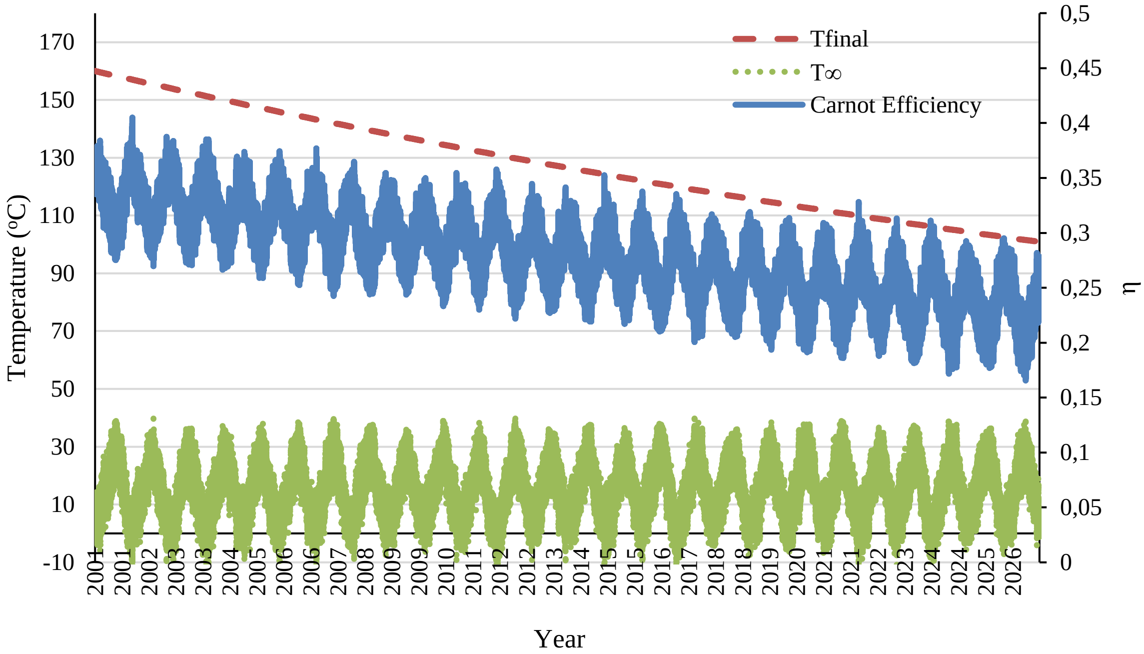


Figure 6. Comparisons of Carnot efficiency, temperature of geothermal resource and ambient temperature between 2001-2026

In Figure (Fig.6), geothermal resource temperature, ambient temperature, and Carnot efficiency changes are presented yearly from 2001 to 2026. The source temperature and Carnot efficiency exhibit a similar linear decrease over the years, whereas the ambient temperature shows relatively smaller annual variations. This phenomenon is due to the slower rate of increase in ambient temperature compared to the rate of decrease in source temperature. In the initial years, the difference between the Carnot efficiency and source temperature is more pronounced; however, this difference diminishes later. This trend is closely associated with the continued decrease in source temperature and the gradual increase in ambient temperature up to 2026, influencing the observed Carnot efficiency. Calculations were made starting from the first hour.

Accordingly, the maximum and minimum values of the source temperature and Carnot efficiencies obtained for each year are given in Table 1.

Table 1. Maximum and minimum values of the source temperature and Carnot efficiency for 2001-2026

Year	T_{source} (ºC)		Carnot efficiency (%)	
	Max.	Min.	Max.	Min.
2001	160.0	157.1	38.3	27.5
2002	157.1	154.2	40.4	26.9
2003	154.2	151.4	38.3	27.0
2004	151.4	148.7	38.5	26.6
2005	148.7	146.0	37.3	25.8
2006	146.0	143.4	37.4	25.2
2007	143.4	140.9	37.6	24.2
2008	140.9	138.3	36.4	24.3
2009	138.3	135.9	35.4	24.3
2010	135.9	133.5	35.4	23.3
2011	133.5	131.1	34.4	22.9
2012	131.1	128.8	35.7	22.1
2013	128.8	126.5	34.4	22.7
2014	126.5	124.3	32.9	21.9
2015	124.3	122.1	35.2	21.7
2016	122.1	119.9	33.7	21.0
2017	119.9	117.8	33.4	20.0
2018	117.8	115.8	31.7	20.5
2019	115.8	113.8	31.9	19.3
2020	113.8	111.8	31.3	19.1
2021	111.8	109.9	30.8	18.5
2022	109.9	108.0	32.8	18.8
2023	108.0	106.2	31.3	18.1
.2024	106.2	104.3	31.0	17.1
2025	104.3	102.6	29.3	17.7
2026	102.6	100.8	29.5	16.5

The highest and lowest geothermal source temperatures calculated for the first year (2001) are 160°C and 157.1°C, respectively. Throughout the life of a geothermal power plant it is seen that the source temperature drops from 160 °C to 100.8 °C. This data is important for the proper management of investments. At the beginning, the temperature drop difference was approximately 2.9 °C, but by the end, it had decreased to 1.8 °C. This change can be attributed to a heat transfer phenomenon driven by the reduction in the temperature gradient. As the source temperature gradually declined over the years, the temperature difference also diminished. However, the highest temperature value recorded for 2026 during this decline was calculated as 102.6°C.

Although the Carnot efficiency generally declines over the plant's lifespan, this decrease is not linear. As shown in the table, the Carnot efficiency values fluctuate. For instance, while an increase in the maximum value is observed from 2001 to 2002, an increase in the minimum value occurs between 2002 and 2003. However, during the same period (2002 to 2003), there is a significant decrease in the maximum value. The maximum and minimum Carnot efficiencies achieved over the plant life are 40.4% and 16.5%, respectively. Maximum Carnot efficiency (40.4%) was achieved in 2002, and minimum efficiency in 2026. These values are directly related to the ambient temperature. Over time, efficiency has decreased due to the decrease in source temperature and the effect of global warming.

4. DISCUSSION AND CONCLUSION

Geothermal energy constitutes a strategic advantage for sustainable energy production in Türkiye. To maximize the efficiency and sustainability of this resource, parameters such as reservoir temperature, depth, pressure, and long-term sustainability must be accurately determined. Additionally, the effects of climatic conditions on energy production should be considered. The average temperature in the region supports the stable and efficient operation of geothermal plants. In this context, accurately defining Denizli's geothermal potential is critical for achieving sustainable energy production and economic development goals. Advanced geothermal modeling, real-time monitoring systems, and environmental impact assessments will play a significant role in increasing the efficiency of energy investments in the region. In this study, the potential of a geothermal energy source located in Denizli district of Türkiye was determined and the environmental effects on the source were examined over time. The results obtained in this context are presented below.

- During the first year of the investment, source temperature was 157.1°C, respectively, with corresponding Carnot efficiencies of 38.3% and 27.5%. By the end of 2026, these values decreased to 102.6°C and 100.8°C for the source temperatures, and 29.5% and 16.5% for the Carnot efficiencies.
- The geothermal resource potential is calculated as 74.97 MWe, and the thermal energy stored in the reservoir is determined as 5.94×1015 J. At the same ambient temperatures, these numbers become larger in sources with higher temperatures.
- The source temperature initially decreased by approximately 2.9°C – 1.7°C, but this difference diminished toward the end. The Carnot efficiency exhibited a fluctuating trend, namely, sometimes decreasing after a year and at other times increasing.
- The maximum and minimum rates of Carnot efficiency vary between 40.4% and 16.5%, respectively. The maximum and minimum rates were achieved in 2002 and 2026, respectively.
- The ambient and source temperatures corresponding to the maximum and minimum rates are 156.3°C (2002) and 101.5°C (2026), respectively. These values take different values at the same source temperature but in different locations due to the environmental temperature.

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