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Thermohydraulic Modeling Study for Bozköy EGS Site (Aksaray), Turkiye, using Carbon Dioxide and Water

Aydın ÇİÇEK[1]*, Ali Cemal BENİM[2,3] and Norbert KLITZSCH[4]

[1] Department of Energy Raw Materials and Survey, General Directorate of the Mineral Research and Exploration of Türkiye, Çukurambar Mahallesi Dumlupınar Bulvarı No:11, 06530 Çankaya, Ankara, Türkiye*
[2] Department of Mechanical and Process Engineering, Düsseldorf University of Applied Sciences, Germany,
[3] Department of Mechanical Engineering, Bursa Technical University, Bursa, Turkey,
[4] Computational Geoscience, Geothermics, and Reservoir Geophysics, RWTH Aachen University, Mathieustr. 30, 52074 Aachen, Germany
E-mail: aydincicek2003@gmail.com

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INTRODUCTION

In Türkiye, the total installed capacity of geothermal power plants has been declared as 1,758 MWe in February 2026 by the Turkish authorities. The total electricity generation from geothermal sources was 11.14 TWh in 2024 (TEİAŞ, 2024), corresponding to 3.14% of the country's total electricity production of 354.60 TWh in the same year (ETKB, 2024). These figures imply an average capacity factor of about 73.3% for the geothermal power plant fleet in 2024. Türkiye's total conventional geothermal potential is estimated as 4,500 MWe (Mertoğlu et al., 2015). In contrast, the total technical potential of enhanced geothermal systems (EGS) at depths of 3-5 km is estimated to exceed 250,000 MWe (Mertoğlu et al., 2015; Schiffer, 2015). Schiffer (2015) further suggested that up to 25,000 MWe of this EGS potential could be realistically developed under a feed-in tariff of 0.105 $/kWh. If such development were achieved, it would correspond to approximately 62% of Türkiye's current annual electricity demand, provided that the technological barriers to EGS deployment can be overcome.

The highest borehole temperature ever recorded in Turkiye was measured as 341 °C at a depth of 3,930 m in the Bozköy geothermal field (BGF) in Aksaray (Figure 1) (3S Kale Energy). The fluid production of the field in the BGF is too low for conventional use, but its otherwise favorable conditions make it suitable for EGS development. The field is currently not in production, but Çiçek et al. (2025a) estimate an EGS capacity of 139-387 MWe for a 50 km^2 license area at a depth of 2-5 km based on Monte Carlo simulations.

Previous studies simulated only water-based geothermal systems (Çiçek et al., 2025b; Chandrasekharam et al., 2023). In the simulations presented here, however, we consider carbon dioxide as a working fluid in addition to water and compare the results for flow rates of 100, 125, and 150 kg/s in terms of efficiency and sustainability.

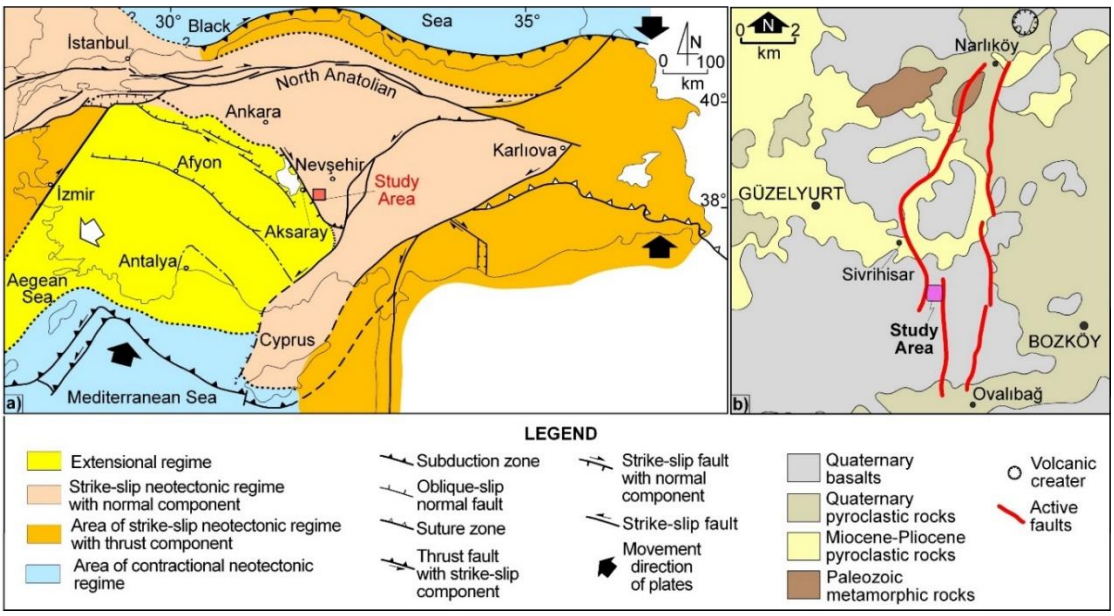


Figure 1. a) Neoteconic map of Türkiye (after Koçyiğit and Özacar, 2003), b) Simplified geological map of the Bozköy field and its vicinity (Redrawn from MTA, 1/500,000 geology map).

1. GEOLOGY OF THE STUDY AREA

The study area's structural configuration is delineated by several prominent tectonic features. To the east, the region is constrained by the Ecemiş/Central Anatolian fault systems, while to the west, it is bordered by the Tuz Gölü fault system. In addition to these major fault systems, several secondary faults have been mapped in the region, including the Keçiboyduran-Melendiz, Hasandağ, Göllüdağ, Derinkuyu, and Yeşilhisar faults. Detailed structural information can be found in Şener et al. (2017).

The specific study area is located in a roughly 13 km long, north-south trending depression bounded by normal faults, about 2 km southeast of the town of Sivrihisar in the district of Güzelyurt in the province of Aksaray in central Turkiye (Figure 1; Çiçek et al., 2025b). The regional stratigraphy has been described in detail by Dönmez et al. (2005) and simplified into five main lithostratigraphic units by Çiçek et al. (2025b): (1) Pre-Mesozoic metamorphic rocks (marble, schist, and gneiss), (2) Upper Cretaceous-Upper Paleocene granitoids, (3) Upper Eocene-Miocene lacustrine sediments, (4) Miocene-Quaternary volcanic rocks, and (5) unconsolidated to weakly consolidated Quaternary clastics and travertines. Although volcanic rocks dominate the surface geology (Figure 1), the pre-Mesozoic metamorphic basement, which crops out approximately 7.5 km north of the site, was selected as the target reservoir for the present modeling, because the existing wells intersect this rock unit within the studied depth range (personal communication, Muzaffer Siyako and Alp Gürün, 2021).

2. METHODOLOGY

The study presented comprises three investigation phases: (1) field sampling, (2) laboratory analysis of physical and thermal properties (density, porosity, specific heat capacity, and thermal conductivity), and (3) thermo-hydraulic (TH) modeling and design optimization. Here we present the methods used in phases (2) and (3).

2.1. Laboratory Analysis

Paleozoic metamorphic rock samples collected from outcrops at four different sites were analyzed for density, porosity, thermal conductivity (TC), and specific heat capacity (Cp). Density and porosity were measured at MTA, Türkiye, following TS 8615/ASTM D2216-NEQ standards. TC and Cp were measured at RWTH Aachen University using a Thermal Conductivity Scanner (TCS) and a Calvet Microcalorimeter C80. Each TC test was repeated twice, and no corrections were applied to porosity or density results (Table 1).

Samples were crushed, oven-dried, and Cp was measured in the temperature range 35-290 °C. The specific heat capacity (Cp) showed negligible sensitivity to stress up to 55 MPa under reservoir conditions. This stress level was estimated from the vertical stress using density data at 3,500 m depth, assuming an isotropic stress state due to limited information on the full stress tensor (i.e., between 300-324 °C) (Waples and Waples, 2004). Hydrostatic pore pressure and saturated rock density from this study were also used during stress predictions. Temperature- and pressure-corrections for TC were applied using felsic correction graphic from Norden et al. (2020) under reservoir conditions.

2.2. Modeling Parameters

The numerical model represents a triplet well system within a 300 × 50 × 300 m domain (Figure 2). The fractured zone (300 × 200 × 4 m) includes 20 parallel stages. While induced fractures are commonly represented as millimeter-scale features in numerical models (Lu and Ghassemi, 2021; Wu et al., 2021), some field observations suggest meter-scale fracture thicknesses in stimulated intervals (Warpinski et al., 1993; Raterman et al., 2017). Thus, a 4 m-thick fracture zone per stage was adopted.

Two symmetry planes, one parallel to the well system and the other to the fracture plane, were defined to model one-quarter of the fracture domain. The simulation domain extends from a depth of 3,350 to 3,650 m, with temperatures of 300 °C at the top and 324 °C at the bottom. Numerical simulations were conducted using ANSYS Fluent 2022 R2 with an equidistant, structured, hexahedral mesh comprising 46,800 cells. A 6-hour time step was employed for the transient analysis. Initial calculations indicate that CO_2 remains in the supercritical phase (sCO_2), whereas water stays in the compressed liquid state. However, the pressure- and temperature-dependent parameters were automatically taken from the ANSYS material library during the simulations. The working fluids were injected at constant 60 °C temperature. Symmetry boundary conditions were applied at the outer walls and wall boundary conditions were assigned to upper and lower walls.

Table 1. Material properties used in this study.

Material	μ (Pa s)	ρ (kg/m^3)	Cp (J/(kg K))	λ (W/(m K))
Water	NIST Table (v.10.0) (Lemmon et al., 2018)			
sCO_2				
Rock	-	2,620	p/T dependent	p/T dependent

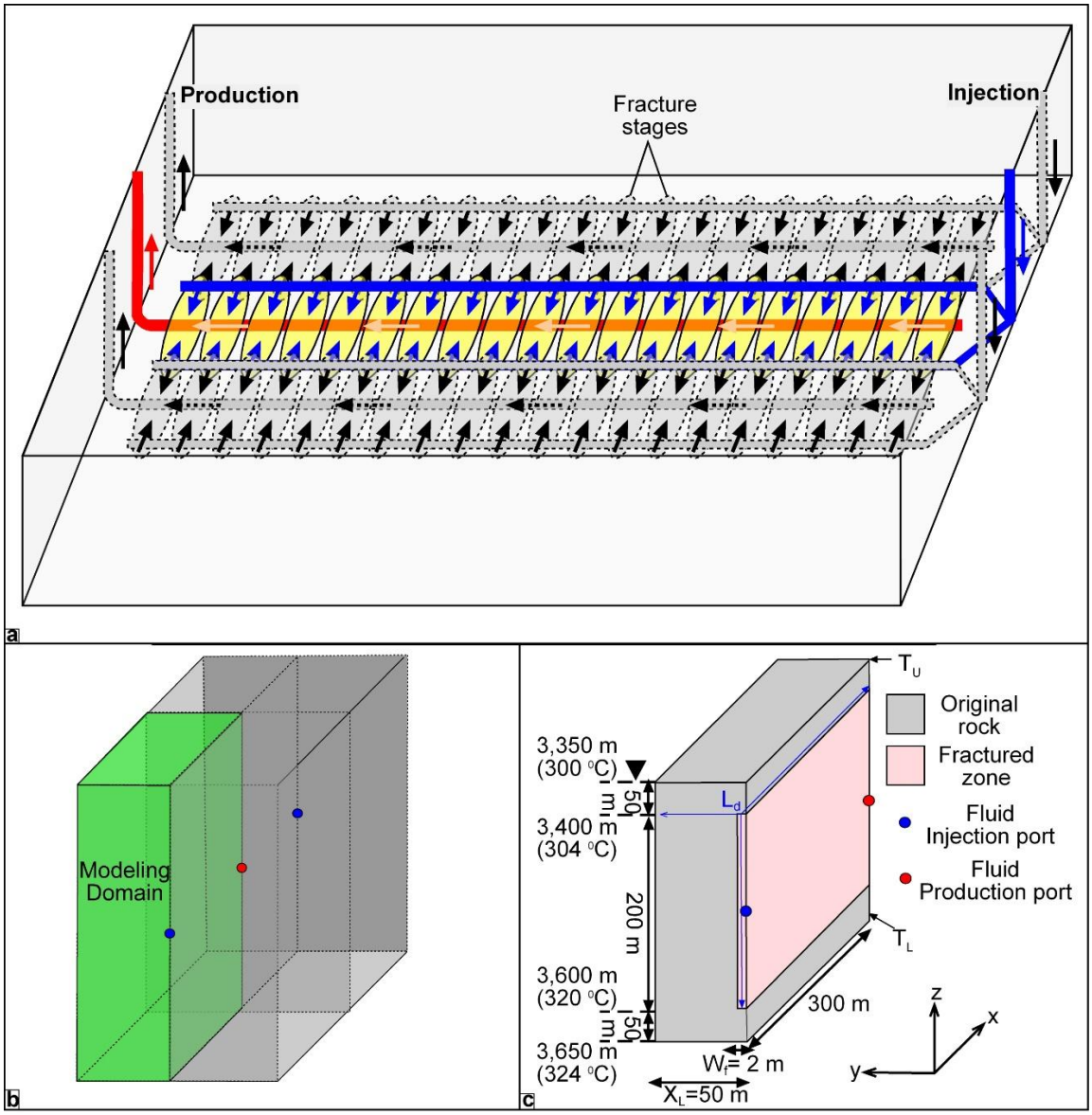


Figure 2. a) General view of the EGS design, b) model geometry of a single fracture, c) the parameters, dimensions and ¼ of a single fracture used during the modeling.

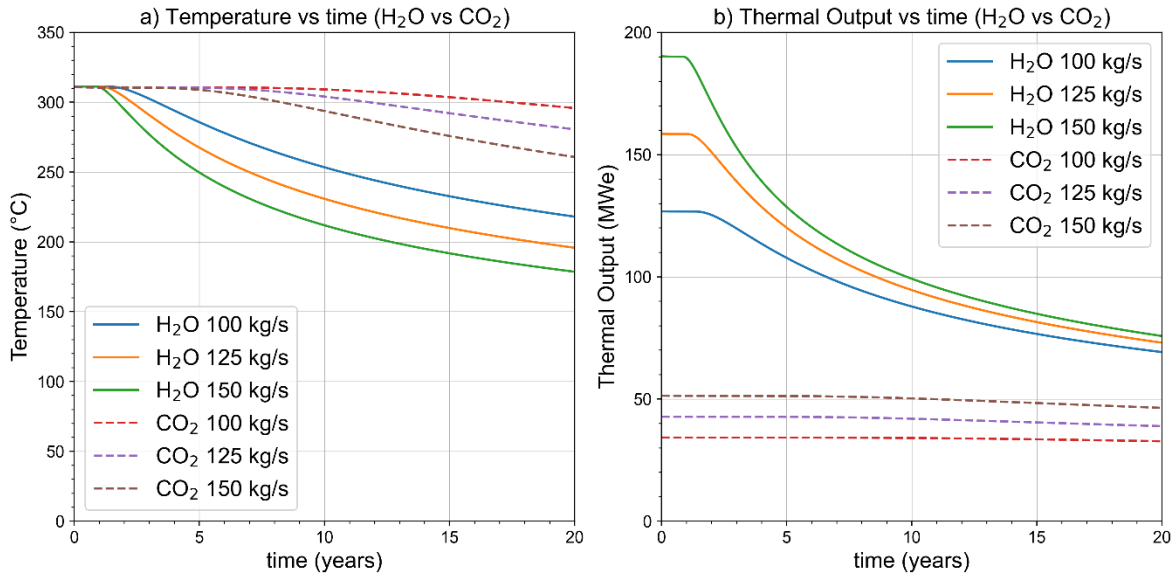


Figure 3. Production temperature (a) and thermal power (b) over time for the working fluids H_2O and CO_2 with different mass flow rates.

3. RESULTS

Simulations with H_2O and sCO_2 as working fluids show different thermo-hydraulic behaviors over a period of 20 years (Figure 3). After 20 years of H_2O circulation, production temperature drops from ~311 °C to 179-218 °C (30-42 %) depending on the flow rate. Thermal breakthrough occurs after ~0.9 year, 1.1 years, and 1.4 years for flow rates of 150 kg/s, 125 kg/s, and 100 kg/s, respectively, with faster cooling observed at higher flow rates. In contrast, sCO_2 circulation exhibits delayed breakthroughs after ~4.2-7.5 years and only 5-9 % temperature loss after 20 years. The lower heat capacity of sCO_2 per unit mass promote a long-term temperature stability.

The trends in thermal output reflect the temperature development. H_2O systems initially generate 127-190 MW_e, with output decreasing by 46-61% over two decades. CO_2 systems initially deliver only 34-51 MW_e but decrease by only 4-15%. As a result, CO_2 systems still have ~85-96% of their original thermal output after 20 years, while H_2O systems only have ~39-54%. The nearly constant ratio of output to temperature for CO_2 confirms its superior power production stability in long-term operation.

Figure 4 illustrates temperature distributions across the fracture plane after 20 years. H_2O cases (a, c, e) display extensive cooled zones propagating from the injection well. Conversely, CO_2 cases (b, d, f) maintain larger hot regions with limited cooling-front advance and enhanced thermal recharge from surrounding rocks. These results demonstrate that CO_2 provides delayed breakthrough and improved long-term thermal stability, whereas H_2O yields substantially higher initial power.

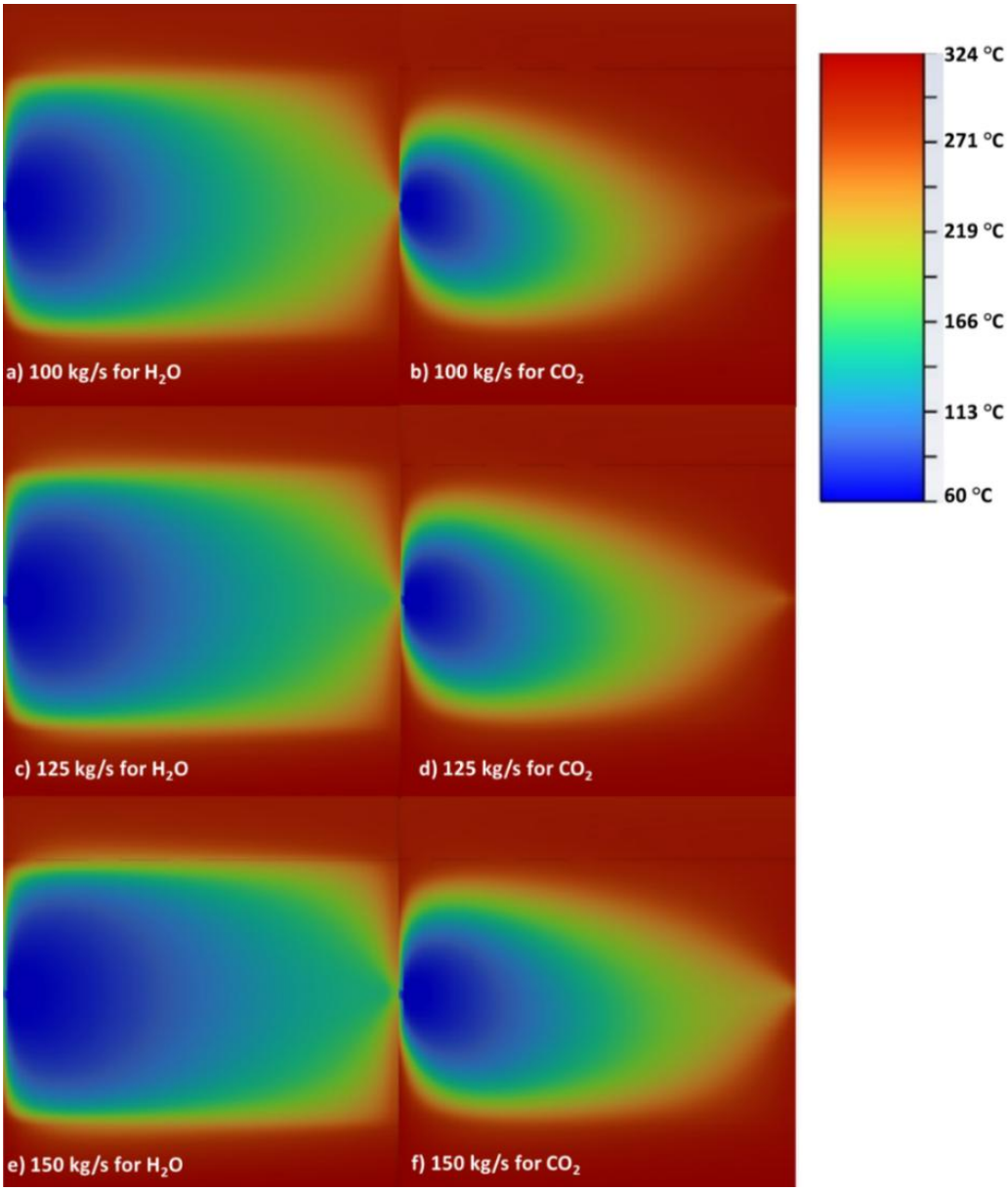


Figure 4. Temperature distribution in the cross-section shown in fig. 2c for various mass flow rates after 20 years of production for H_2O (a, c, e) and CO_2 (b, d, f).

4. CONCLUSION

Thermohydraulic simulations indicate that the choice of working fluid strongly affects the thermo-hydraulic response of the Bozköy EGS system. H_2O provides higher initial power (127-190 MW_e) but experiences faster cooling (30-42 %) and early breakthrough within 0.9-1.4 years. In contrast, CO_2 shows delayed breakthrough (4.2-7.5 years) and minimal temperature loss (5-9 %) over 20 years. Owing to its lower heat capacity, CO_2 maintains long-term thermal stability. While H_2O maximizes short-term output, CO_2 ensures more efficient and sustainable long-term performance for EGS operations at Bozköy and similar high-temperature sites.

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