Kırklareli Üniversitesi
Mühendislik ve Fen Bilimleri Dergisi
Cilt 10, Sayı 2, 282-293, 2024

Kırklareli University
Journal of Engineering and Science
Volume 10, Issue 2, 282-293, 2024

Research Article DOI: 10.34186/klujes.1576527

Effect of Different Fluid Types on Cycle Performance in Electricity Generation with Geothermal Energy

Oguzhan Erbas[1*]

[1]*Department of Mechanical Engineering, Faculty of Engineering, Kutahya Dumlupinar University, Kutahya, Turkiye*

Received: 30.10.2024, Accepted: 8.11.2024, Published: 26.12.2024

ABSTRACT

Geothermal energy is a naturally renewable resource and can produce electricity and heat without harming the environment with less carbon dioxide emissions than fossil fuels. This makes it an environmentally friendly option. Our country is located on an active tectonic belt and has an important position in the world in terms of geothermal energy resources. For this reason, we have a high potential to benefit from geothermal resources. The design of the geothermal energy electricity generation system (turbine, heat exchanger, fluid properties, etc.) also plays a critical role in terms of efficiency. The system should be optimized according to conditions such as temperature and pressure. In this study, electricity production performances were compared for different fluid types in the secondary cycle, turbine efficiency and wellhead temperature in an energy conversion plant using a geothermal fluid with a source temperature of 195 ^{0}C.

Keywords: Geothermal energy, Electricity production, Fluid type, Performance analysis

Jeotermal Enerji ile Elektrik Üretiminde Farklı Akışkan Türlerinin Çevrim Performansına Etkisi

ÖZ

Jeotermal enerji, doğal olarak yenilenen bir kaynak olup, fosil yakıtlara göre daha az karbondioksit emisyonu ile çevreye zarar vermeden elektrik ve ısı üretebilir. Bu da onu çevre dostu bir seçenek haline getirmektedir. Ülkemiz, aktif bir tektonik kuşak üzerinde yer almaktadır ve jeotermal enerji kaynakları bakımından dünya genelinde önemli bir konuma sahiptir. Bu sebeple jeotermal kaynaklardan faydalanma potansiyelimiz yüksektir. Jeotermal enerji ile elektrik üretim sistemi (türbin, ısı eşanjörü, akışkan özellikleri vb.) tasarımı da verimlilik açısından kritik bir rol oynamaktadır. Sistem, sıcaklık ve basınç gibi koşullara göre optimize edilmelidir. Bu çalışmada da; 195 ^{0}C kaynak sıcaklığı olan bir jeotermal akışkan kullanılan enerji dönüşüm santralinde, ikincil çevrimdeki farklı akışkan tipleri, türbin verimi ve kuyu başı sıcaklığı için elektrik üretim performansları karşılaştırılmıştır.

Anahtar Kelimeler: Jeotermal enerji, Elektrik üretimi, Akışkan tipi, Performans analizi

* *Correspondimg Author: Oguzhan Erbas*
oguzhan.erbas@dpu.edu.tr

1. INTRODUCTION

The global energy transformation is facing significant challenges. In order to achieve sustainable development goals on a national and global scale, it is extremely necessary to increase the use of renewable resources. Sustainable development requires the evaluation of resources with high efficiency in a manner compatible with the environment. In Turkey, a country aiming to become a member of the European Union; European Union standards should be taken into consideration in energy policies, structuring of energy management and legal regulations related to energy. In the building sector, enhancing efficiency is crucial for facilitating the energy transition. There is an increasing need for adopting efficient appliances, as well as rapidly renovating and refurbishing existing buildings. Projections suggest that to align with a pathway compatible with limiting temperature rise to 1.5°C, the share of renewables in this sector must increase to 86% by 2050. This includes highly decarbonized electricity, district cooling and heating, bioenergy, and direct use of renewables, such as solar thermal and geothermal energy (IRENA, 2023; Dinçer, 2020).

Direct use of geothermal energy refers to the ready use of heat energy without being converted into other forms of energy such as electrical energy. The main areas of direct use are; heating of swimming pools, balneology, space heating and cooling including regional heating, agricultural applications (greenhouse heating), aquaculture applications, industrial processes and heat pump applications(Arslan, 2010; Tuğcu, 2016). The simplest and cheapest cycle used for electricity production is the Direct-Steam Cycle. Direct-Steam (or dry steam) power plants are used in steam-heavy reservoirs. Dry, saturated or slightly superheated steam is obtained from wells. Steam carries non-condensable gases of various compositions and concentrations. This steam obtained from the wells is transported through pipes and used directly in the impulse/reaction type turbine in the power plant, and the waste steam is released into the atmosphere (Tuğcu, 2016; Rašković, 2013).

In a Binary power plant, the thermal energy of the geothermal fluid is transferred to a secondary working fluid to be used in a suitable conventional Rankine cycle via a heat exchanger. The geothermal fluid does not come into contact with the moving parts of the power plant and therefore erosion formation is minimized. Binary power plants are advantageous in certain conditions such as geothermal fluids with high dissolved gas content, high corrosivity or scaling potential. Naturally, another problem arises when the liquid geothermal fluid suddenly turns into vapor at the well exit, but this problem can be prevented by using downhole pumps (submersible pumps). In most Binary power plants, such pumps are used and the geothermal fluid remains in the liquid phase throughout the power plant (Zinsalo, 2022; Kabeyi, 2019).

Geothermal waters are waters that either seep down from the surface to the underground or emerge from magma. Geothermal energy is a type of energy formed by the heat accumulated in the workable depths of the earth's crust. This heat reaches the surface naturally in the form of hot water sources and steam or in the form of hot water extracted by drilling, hot water + steam and steam. It can also be used economically directly or by converting it into other types of energy.

To limit global warming to 1.5°C, we must cut carbon dioxide (CO_2) emissions by about 37 gigatonnes from 2022 levels and achieve net-zero emissions in the energy sector by 2050. Although some progress has been made, there are still significant gaps in deploying energy transition technologies needed to meet the Paris Agreement goals. Achieving a 1.5°C pathway requires a complete transformation in energy consumption and production (IRENA, 2023). From 2013 to 2020, roughly 75% of global renewable energy investments came from the private sector, with 83% of solar financing from private capital. In contrast, geothermal and hydropower relied heavily on public funding, with only 32% and 3% of investments from private sources, respectively (IRENA and CPI, 2023). To encourage more equitable investment, stronger public sector intervention is necessary to allocate funding toward countries and technologies that are often underrepresented. Expanding global electricity generation capacity by 2030 and 2050 is essential to achieve the 1.5°C Scenario (Figure 1).

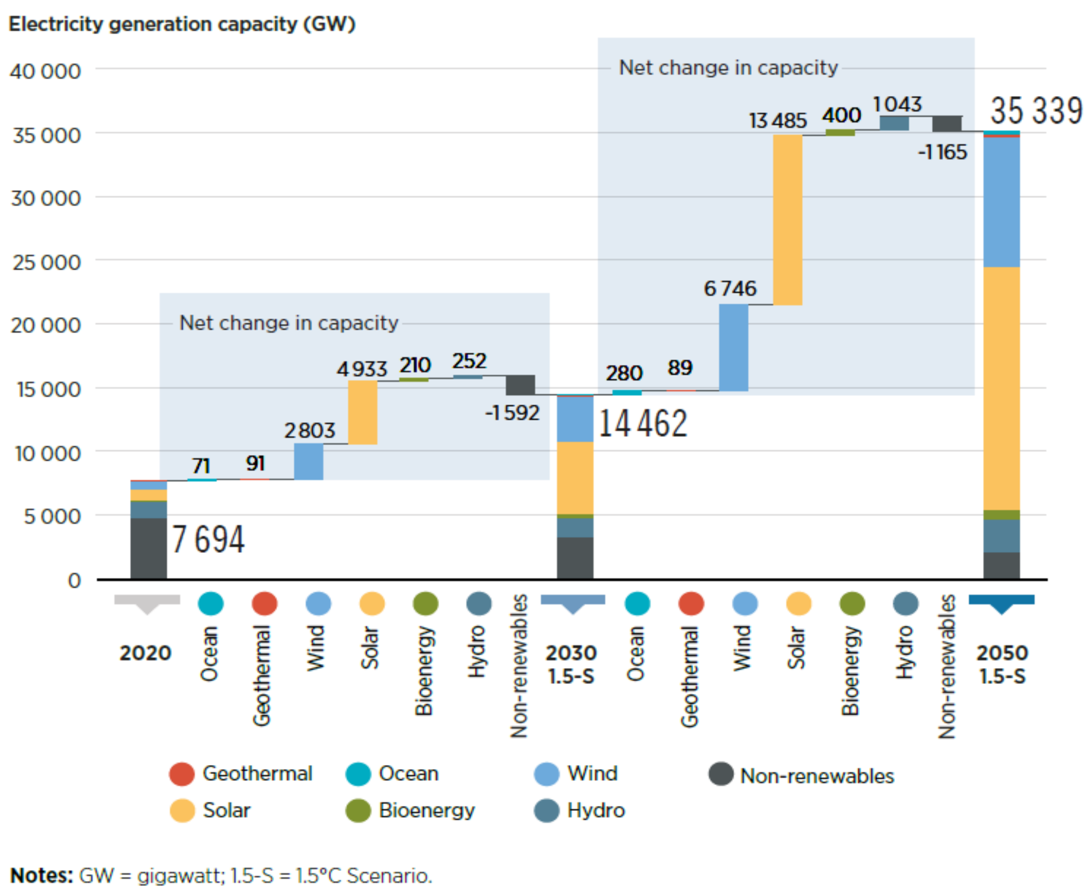

Figure 1. Total global electricity generation capacity needed (IRENA, 2023).

In the short term, rising fossil fuel prices make renewable energy solutions more attractive. Wind and solar power have become highly competitive with gas-fired power generation. Additionally, the increase in fossil fuel prices has narrowed the cost gap between biofuels, biomethane, and fossil-based transport fuels. This shift has also improved the cost competitiveness of bioenergy, as well as solar, geothermal, and heat pumps powered by renewable electricity (Bayer, 2013; Chitgar, 2023).

Our country ranks sixth in the world and first in Europe in terms of geothermal energy capacity. Thanks to its geological structure, there are geothermal resources at various temperatures across nearly all regions. These resources are currently utilized for multiple purposes, including electricity generation, residential heating, greenhouse farming, and health tourism. It is essential to evaluate this natural resource with effective, environmentally friendly practices that consider the needs of local communities, aiming for overall development. This study compares the electricity production performance of different fluid types and turbine efficiencies in the secondary cycle of a geothermal energy conversion plant operating at a wellhead temperature of 195 °C.

2. ENERGY AND EXERGY PROCESS IN GEOTHERMAL ENERGY CONVERSION SYSTEM

Due to the limited primary energy resources and the rapid increase in energy costs, exergetic analyses have gained great importance in determining energy losses in thermal systems. If exergy losses decrease, i.e. exergy efficiency increases, the destruction, resource consumption and lost exergy emissions that will occur in the process will decrease inversely proportional. In a steady-state, steady-flow process, mass, energy, entropy, and exergy balance equations determine work and heat interactions, exergy decrease, and efficiencies. The mass balance is presented in rate form (Arslan, 2010).

$$\sum \dot{m}_{\mathrm{in}} = \sum \dot{m}_{\mathrm{out}} \tag{1}$$

The mass flow rate is defined with 'in' for the inlet and 'out' for the outlet. The energy balance states that total energy inputs must equal total energy outputs.

$$\sum \dot{E}_{\mathrm{in}} = \sum \dot{E}_{\mathrm{out}} \tag{2}$$

This equation clearly expresses the first law of thermodynamics and can be rewritten, ignoring kinetic and potential energy changes, as follows:

$$\dot{Q} - \dot{W} = \sum \dot{m}_{\mathrm{in}}\, h_{\mathrm{in}} - \sum \dot{m}_{\mathrm{out}}\, h_{\mathrm{out}} \tag{3}$$

Heat and work are the main transfers across a system boundary. Without electricity, magnetism, surface tension, or nuclear reactions, total exergy divides into four components: physical, kinetic, potential, and chemical exergy (Arslan, 2010).

The overall exergy balance is fundamentally important and can be stated as follows:

$$\dot{E}x_{\text{heat}} + \dot{E}x_{\text{work}} + \dot{E}x_{\text{mass, in}} - \dot{E}x_{\text{mass , out}} = \dot{E}x_{\text{d}} \tag{4}$$

In this context, $\dot{E}x_{\text{heat}}$ and $\dot{E}x_{\text{work}}$ represent the exergy components from heat and work interactions, while $\dot{E}x_{\text{mass}}$ and $\dot{E}x_{\text{mass, out}}$ refer to those from mass transfer across the system boundary. $\dot{E}x_{d}$ denotes the destroyed exergy.

$$\dot{E}x_{\text{heat}} = \sum\left(1 - \frac{T_0}{T_{\text{k}}}\right)\dot{\text{Q}}_{\text{k}} \tag{5}$$

$$\dot{E}x_{\text{work}} = \dot{W} \tag{6}$$

$$\dot{E}x_{\text{mass, in}} = \sum(\dot{m}\psi)_{\text{in}} \tag{7}$$

$$\dot{E}x_{\text{mass , out}} = \sum(\dot{m}\psi)_{\text{out}} \tag{8}$$

Where $\dot{Q}_{\text{k}}$ represents the heat transfer rate through the boundary at temperature T_{k}, located at k, ψ is defined as the flow (specific) exergy as follows:

$$\psi = (h - h_0) - T_0(s - s_0) \tag{9}$$

$$\dot{I} = \dot{E}x_{\text{d}} = T_0\dot{S}_{\text{gen}} \tag{10}$$

Energy and exergy efficiencies are clearly defined by the following equations(Arslan, 2010):

$$\eta = \frac{\dot{E}_{\text{out}}}{\dot{E}_{\text{in}}} \tag{11}$$

$$\varepsilon = \frac{\dot{E}x_{\text{out}}}{\dot{E}x_{\text{in}}} \tag{12}$$

3. GEOTHERMAL POWER PLANT MODEL AND PROCESS FLOW CHARACTERISTICS

In the cycle shown in Figure 2. and optimized with the “THERMOFLEX” energy conversion system design program, steam obtained from the geothermal source underground is directed to a heat exchanger. While the geothermal fluid loses heat on one side of the heat exchanger, it heats the secondary fluid on the other side. The secondary fluid is a liquid with a low boiling point and therefore evaporates at lower temperatures. This liquid evaporates after receiving heat and this steam is directed to the turbine. The vapor of the organic liquid rotates the turbine and generates electricity. Then this vapor becomes liquid again through a cooling system (heat exchanger-condenser). The cooled secondary fluid returns to the initial heat exchanger and the process starts again (Bu, 2013; Luo 2012).

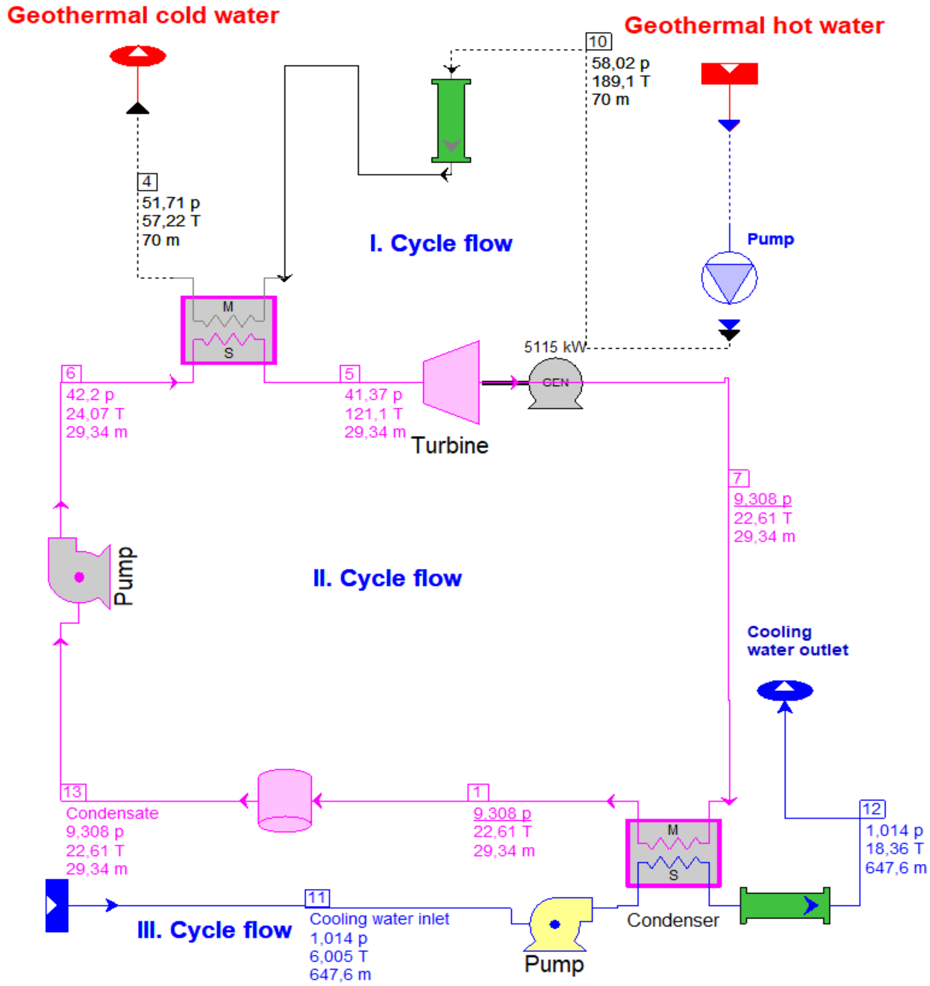

Figure 2. Electricity generation work flow chart with geothermal energy

In Binary cycle systems that generate electricity from geothermal energy, the dry step efficiency plays an important role in the design of the cooling turbine. The dry step efficiency indicates how effectively the turbine converts water vapor. Increasing this efficiency can positively affect the overall efficiency and energy output of the system. A high dry step efficiency means more energy production. This allows the turbine to produce more work and therefore to benefit more from the potential of the geothermal resource. In binary cycle systems, the efficiency of the cooling turbine also affects the heat exchanger performance. A better dry step efficiency helps the heat exchanger to operate more efficiently, thus increasing the overall efficiency of the system (Heberle, 2010 ; Beckers , 2022).

The properties of the secondary fluid directly affect the efficiency and performance of the binary cycle power plant, increasing the energy production capacity. Therefore, the selection and design of the secondary fluid is a critical element for the efficiency of geothermal power plants. Seven different types of fluids (Ammonia, R22, Propane, SO_2, R12, R134a, R21) were compared in terms of electricity production performance in the designed geothermal power plant model. The best fluid in terms of net electrical efficiency (%), net obtained power (kW) and plant auxiliary (kW) was ammonia. A low "plant auxiliary (kW)" value positively affects the efficiency, costs and environmental impacts of the plant. Therefore, it is aimed to minimize auxiliary energy consumption in energy production processes (Liu, 2013 ; Li, 2022).

4. RESULTS

In these types of energy conversion plants, the selected secondary fluid has a low boiling point, allowing it to evaporate at low temperatures. This makes it possible to produce effective energy even at the lower temperatures of the geothermal source. The high heat capacity of the secondary fluid allows it to store and use more heat, while a fluid with low viscosity reduces the flow resistance in the system. This enables components such as pumps and turbines to operate more efficiently. Again, the fact that this fluid is non-corrosive extends the life of the turbine and other system components and reduces maintenance requirements. Table 1. shows system performance values according to different fluid types used in the secondary cycle in the electricity production process from geothermal energy.

Table 1. Effect of Different Fluid Types on Optimizing Performance in Electricity Generation from Geothermal Energy

	Case 1	**Case 2**	**Case 3**	**Case 4**	**Case 5**	**Case 6**	**Case 7**
Type of fluid used in energy conversion	**Ammonia**	**R22**	**Propane**	**SO_2**	**R12**	**R134a**	**R21**
Plant gross power (kw)	5458	5813	5889	3921	5655	5243	2261,6
Plant net power (kw)	5073	4923	4791	3417	4356	4229	1764,7
Plant auxiliary (kw)	385	889,2	1097,5	504,6	1299,4	1014,7	496,9
Miscellaneous plant auxiliary load (kw)	54,58	58,13	58,89	39,21	56,55	52,43	22,62
Plant gross heat rate (LHV) (kj / kwh)	27140	25487	25158	29283	26195	28253	29574
Plant net electric efficiency (LHV)	12,33	11,96	11,64	10,71	10,59	10,28	9,49
Plant net heat rate (LHV) (kj / kwh)	29200	30090	30921	33608	34009	35033	37900

The dry step efficiency affects the ability to optimize the temperature difference at which the turbine operates. Higher efficiency can increase energy production even at low temperature differences. At the same time, high dry step efficiency can affect the turbine size and system costs. The increased efficiency can allow for the use of smaller and lower cost turbines. In addition, higher efficiency means less energy loss and therefore lower environmental impacts. This allows for more sustainable use of geothermal resources.

In the cycle where ammonia is used as a fluid, the change of some important parameter values for different values of the refrigerant turbine design point dry step efficiency is shown in Table 2.

Table 2. Variation of parameter values for different values of turbine design point dry step efficiency (Ammonia)

	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7
Turbine design point dry step efficiency (%)	88	86	84	82	90	92	94
Plant gross power (kW)	5458	5333	5209	5084	5583	5708	5833
Plant net power (kW)	5073	4950	4826	4702	5197	5321	5445
Plant auxiliary (kW)	385	383,8	382,7	381,5	386,1	387,3	388,5
Miscellaneous plant auxiliary load (kW)	54,58	53,33	52,09	50,84	55,83	57,08	58,33
Plant gross heat rate (LHV) (kj / kWh)	27140	27776	28442	29141	26533	25952	25396
Plant net electric efficiency (LHV)	12,33	12,03	11,73	11,43	12,63	12,93	13,23
Plant net heat rate (LHV) (kj / kWh)	29200	29930	30698	31506	28504	27841	27208

In this system that produces electricity with geothermal energy, the mechanical efficiency of the turbine is also an important factor that directly affects the overall performance of the system. The mechanical efficiency of the turbine indicates how much of the energy input by the turbine can be converted into mechanical energy. High mechanical efficiency increases the efficiency of the system and provides more electricity production. In other words, it allows the energy obtained from geothermal resources to be converted into electrical energy more effectively. This increases the overall efficiency of the system and means more energy production. It reduces costs and environmental impacts while increasing energy production. Therefore, optimizing the mechanical efficiency of the turbine during the design phase is of critical importance. In the cycle where ammonia is used as the fluid, the changes of some important parameter values for different values of the turbine mechanical efficiency are shown in Table 3.

Table 3. Variation of parameter values for different values of turbine mechanical efficiency (Ammonia)

	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7
Turbine mechanical efficiency	99	97	95	93	91	89	87
Plant gross power (kW)	5458	5347	5236	5125	5014	4903	4792
Plant net power (kW)	5073	4963	4854	4744	4634	4524	4414
Plant auxiliary (kW)	385	383,9	382,8	381,7	380,5	379,4	378,3
Miscellaneous plant auxiliary load (kW)	54,58	53,47	52,36	51,25	50,14	49,03	47,92
Plant gross heat rate (LHV) (kj / kWh)	27140	27704	28292	28905	29545	30213	30913
Plant net electric efficiency (LHV)	12,33	12,06	11,79	11,53	11,26	10,99	10,73
Plant net heat rate (LHV) (kj / kWh)	29200	29847	30523	31230	31971	32748	33563

The increase in the temperature of the geothermal fluid positively affects the efficiency of binary cycle power plants. Figure 3. and Figure 4. show the effect of the geothermal source on the system with the increase in the wellhead temperature. As the temperature of the geothermal fluid increases, the heat energy obtained from this fluid increases. This allows the organic fluid in the cycle to vaporize at higher temperatures and thus produce more energy. As a result, the overall efficiency increases. At the same time, the high temperature increases the vapor pressure of the organic fluid. This helps the turbine to produce more energy.

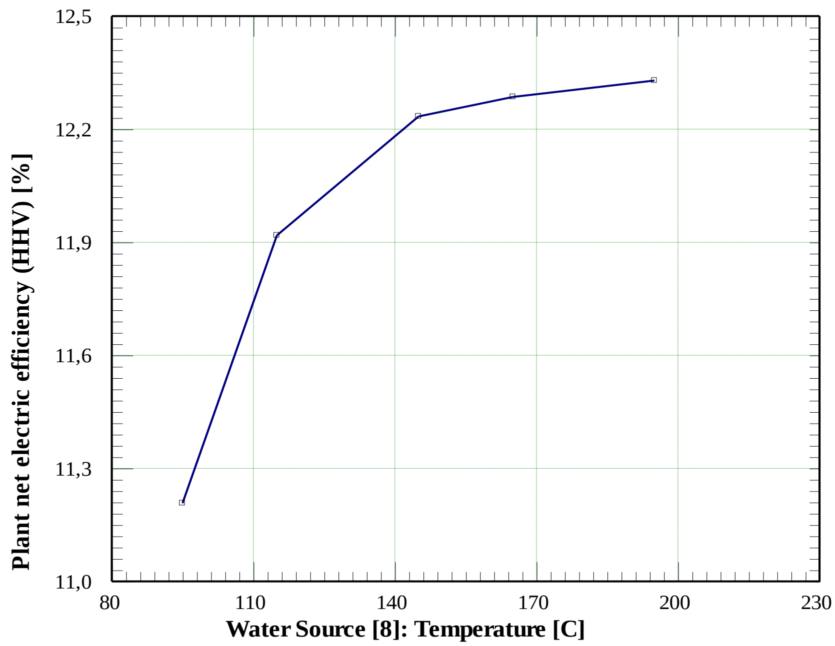

Figure 3. Effect of geothermal source temperature on net electricity efficiency

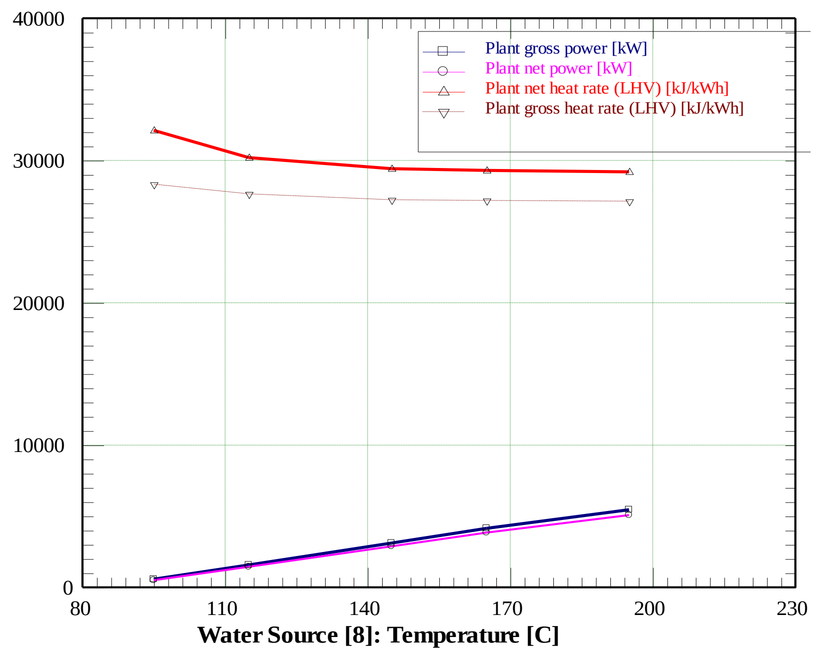

Figure 4. Effect of geothermal source temperature on power and heat rate in the system

5. CONCLUSION

Increased dry step efficiency in the turbine and increased geothermal flow binary cycle results in greater energy production and system efficiency. Therefore, paying attention to parameter selection at the design stage makes a critical contribution. Geothermal energy is expected to become more widely used in the coming years due to its numerous advantages. One of the main reasons for this is the role of geothermal power plants in providing baseload electricity generation. As renewable energy sources such as solar and wind continue to gain popularity, the importance of power plants that offer both renewable energy and baseload support, such as geothermal power plants, will increase.

Geothermal power plants generally have a lifespan of 20 to 50 years. However, this period may vary depending on the status of the resources, the design of the plant, maintenance practices and technological developments. In a new plant, efficiency is usually high. Over time, the pressure and temperature of the hot water and steam resources may decrease. This may affect the efficiency of the plant. Performance can be maintained with regular maintenance, resource management and, if necessary, system renewals. The most suitable type of plant for hydrothermal resources is dry steam plants or hot water plants (binary cycle). Such plants are systems where hot water is directly converted to steam or energy is transferred to another liquid through a heat exchanger. Geothermal steam sources are generally sources containing steam at high temperature and pressure. In this case, dry steam plants are the most suitable option. Such plants are systems where steam is directly used in turbines.

Geothermal energy can be integrated with other renewable energy sources in various ways. Geothermal energy can be integrated with wind and solar energy, increasing continuity in energy production. Especially during periods when solar energy is high, the geothermal energy system comes into play and helps maintain the balance in the grid. Geothermal energy systems can also work together with thermal energy storage systems. This allows hot water to be used during times of increased energy demand, especially through hot water storage systems. Geothermal power plants can also be integrated for both electricity and heat production (in combined cycle power plants). This increases energy efficiency and optimizes total energy output. Geothermal power plants can be sensitive to seismic activity due to the use of underground water and steam resources. Drilling operations for geothermal energy can change underground pressure, which can trigger seismic activity. Similarly, the injection of cold-water underground can change underground temperatures and pressure, which can affect seismic activity.

Information Note: This study was supported within the scope of Kutahya Dumlupınar University Scientific Research Project, No. 2024 – 44.

CONFLICT OF INTEREST DECLARATION

There is no conflict of interest between the authors.

CONTRIBUTIONS OF THE AUTHORS

O.E.: Methodology, software, validation, investigation, resources, writing original draft preparation.

REFERENCES

IRENA (2023), World Energy Transitions Outlook 2023: 1.5°C Pathway, Volume 1, International Renewable Energy Agency, Abu Dhabi.

Dinçer, İ., & Ezan, M. E. H. M. E. T. (2020). Tuba-geothermal energy technologies report.

Arslan, O., & Kose, R. (2010). Exergoeconomic optimization of integrated geothermal system in Simav, Kutahya. *Energy Conversion and Management*, *51*(4), 663-676.

Tuğcu, A., Arslan, O., Köse, R., & Yamankaradeniz, N. (2016). Thermodynamic and economic analysis of geothermal supported absorption cooling system: Simav example. Journal of Thermal Science and Technology, 36(1), 143-159.

Rašković, P., Guzović, Z., & Cvetković, S. (2013). Performance analysis of electricity generation by the medium temperature geothermal resources: Velika Ciglena case study. *Energy*, *54*, 11-31.

Zinsalo, J. M., Lamarche, L., & Raymond, J. (2022). Performance analysis and working fluid selection of an Organic Rankine Cycle Power Plant coupled to an Enhanced Geothermal System. *Energy*, *245*, 123259.

Kabeyi, M. J. B. (2019). Geothermal electricity generation, challenges, opportunities and recommendations. *International Journal of Advances in Scientific Research and Engineering (ijasre)*, *5*(8), 53-95.

Bayer, P., Rybach, L., Blum, P., & Brauchler, R. (2013). Review on life cycle environmental effects of geothermal power generation. *Renewable and Sustainable Energy Reviews*, *26*, 446-463.

Chitgar, N., Hemmati, A., & Sadrzadeh, M. (2023). A comparative performance analysis, working fluid selection, and machine learning optimization of ORC systems driven by geothermal energy. *Energy Conversion and Management*, *286*, 117072.

Bu, X., Wang, L., & Li, H. (2013). Performance analysis and working fluid selection for geothermal energy-powered organic Rankine-vapor compression air conditioning. *Geothermal Energy*, *1*, 1-14.

Luo, C., Huang, L., Gong, Y., & Ma, W. (2012). Thermodynamic comparison of different types of geothermal power plant systems and case studies in China. *Renewable energy*, *48*, 155-160.

Heberle, F., & Brüggemann, D. (2010). Exergy based fluid selection for a geothermal Organic Rankine Cycle for combined heat and power generation. *Applied Thermal Engineering*, *30*(11-12), 1326-1332.

Beckers, K. F., Rangel-Jurado, N., Chandrasekar, H., Hawkins, A. J., Fulton, P. M., & Tester, J. W. (2022). Techno-economic performance of closed-loop geothermal systems for heat production and electricity generation. *Geothermics*, *100*, 102318.

Liu, Q., Duan, Y., & Yang, Z. (2013). Performance analyses of geothermal organic Rankine cycles with selected hydrocarbon working fluids. *Energy*, *63*, 123-132.

Li, T., Liu, Q., Gao, X., Meng, N., & Kong, X. (2022). Thermodynamic, economic, and environmental performance comparison of typical geothermal power generation systems driven by hot dry rock. *Energy Reports*, *8*, 2762-2777.