




PERFORMANCE EVALUATION OF AFYON GEOTHERMAL POWER PLANT WITH LOW GRADE ENERGY SOURCES

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(Geliş/Received: 30.09.2019; Kabul/Accepted in Revised Form: 13.01.2020)

ABSTRACT: Exergoeconomic performance evaluation of 2700 kW binary cycle design geothermal power plant in western Turkey is conducted using actual plant operating data, and potential improvements are identified. Afyon Geothermal Power Plant is thermodynamically modeled in a computer environment using current working parameters in a comprehensive way for the use of geothermal energy in electricity generation. To simulate the plant during thermodynamic conditions with exergoeconomic analysis, the Engineering Equation Solver (EES) software is used. Geothermal water temperature and mass flow rate of the plant are 110°C, and 150 kg/s, respectively. Energy and exergy efficiencies of the plant are calculated as 10.4%, and 29.7%. The potential annual revenue of geothermal electricity is calculated to be 2,880,277 \$/yr. The exergetic cost of the electricity from the plant is calculated as 0.0233 \$/kWh, respectively.

Key Words: *Geothermal power plant, thermodynamic analysis, exergoeconomic analysis*

Düşük Enerji Seviyeli Kaynakla Çalışan Afyon Jeotermal Güç Santralinin Performans Değerlendirilmesi

ÖZ: Türkiye'nin batısındaki 2700 kW'lık binary jeotermal santralinin termoekonomik performans değerlendirmesi ve mevcut işletme verileri kullanılarak gerçekleştirilmiş ve potansiyel iyileştirmeler tespit edilmiştir. Afyon Jeotermal Santrali, elektrik üretiminde jeotermal enerjinin kullanımı için mevcut çalışma parametrelerini kapsamlı bir şekilde kullanarak bilgisayar ortamında termodinamik olarak modellenmiştir. Santralin modellenmesinde termodinamik koşullar altında ekergoekonomik analiz için Mühendislik Denklem Çözme (EES) yazılımı kullanılmıştır. Jeotermal suyun sıcaklığı ve kütleli debisi sırasıyla 110°C ve 150 kg/s'dir. Santralin enerji ve ekserji verimliliği %10.4 ve %29.7 olarak hesaplanmıştır. Yıllık ortalama jeotermal elektrik geliri 2,880,277 \$/yıl olarak hesaplanmaktadır. Santralden üretilen elektriğin ekserjetik maliyeti ise 0.0233 \$/kWh olarak hesaplanmaktadır.

Anahtar Kelimeler: *Jeotermal enerji santrali, termodinamik analiz, eksergoekonomik analiz*

1. INTRODUCTION

Today, energy consumption appears to be directly related to the level of population and degree of industrialization of the country. Those countries that have abundant supplies of energy available to them have realized substantially higher rates of industrial growth. In many cases, the availability low-cost energy has led to the inefficient utilization of energy and to harmful environmental effects. However, it is obvious that in order to raise the level of the world population, the present rate of energy consumption must be greatly expanded. Currently, the major energy source of the world is a conventional energy source called fossil fuels. This source supplies about 70 percent of the total fuel of energy in the world. The other 30 percent is renewable energy sources (Kasaei *et al.*, 2017). The utilization of renewable energy sources is

very attractive because they are continuing or non depletion sources of energy and because they are relatively non pollutant a very important consideration. In the industrial application, energy is the most important material to solve the problem of requirements. Especially developing countries need too much energy consumption that machines work with consumed in the industrial applications. For that reason, this problem should be solved by the alternative energy resources. Currently, the most commonly used energy resources are the fossil-based energy sources in the world. These conditions bring with some problems. Some of these are the depletion of fossil fuels, the harmful effect on the environment and human health. The exhaust of the plants is one of the major contributors to the world's air pollution problem. Four major emissions produced by fossil-based energy sources using are hydrocarbons, carbon monoxide, oxides of nitrogen, and solid particles (Balcilar *et al.*, 2018). Two methods are used to reduce the harmful effects of fossil fuel emissions. One is to improve the technology of energy conversion systems and fuels better combustion occur and fewer emissions are produced. The second method is alternative energy resources. For instance, this issue has led us to alternative energy sources, which are renewable and sustainable energies. Today, the best known alternative energy sources are renewable energy sources which wind, solar, hydro, geothermal, and biomass are the most common. Produced renewable electricity must be economically competitive level with against fossil-based energy resources. Geothermal binary cycle power plants tend to have low environmental impacts because the geothermal water which can contain toxic gases is not sprayed to the atmosphere, expect during well drilling (Yilmaz, 2017).

In the open literature, some relevant studies have been conducted on geothermal energy for electricity production. Kanoglu (2002) was performed an exergy analysis of 12.4 MW existing binary geothermal power plant. The exergetic efficiency of the plant was found to be 29.1% based on the exergy of the geothermal water at the inlet state, and 34.2% based on the exergy loss of the preheater system. The corresponding thermal efficiencies for the plant were calculated to be 5.8 and 8.9%, respectively. DiPippo (2007) was reviewed as to its appropriateness to serve as the ideal model for geothermal binary power plants. He showed that the Carnot cycle sets a theoretical upper limit on the thermal efficiency of these plants. He found that actual binary plants can achieve relative efficiencies as high as 85%. Yari (2010) was proposed an exergetic analysis of various types of geothermal power plants. The maximum thermal efficiency was found to be related to the binary cycle with R123 as the working fluid and was calculated to be 7.65%. Karadas *et al.* (2015) were conducted a regression analysis of 7.35 MW existing binary geothermal power plant using actual plant data to assess the plant performance. According to their analyses, since 2009, the plant performance was started to decline with 270 kW electricity generation capacities. Wang *et al.* (2015) performed a thermodynamic analysis and optimization of a flash-binary geothermal plant. The effects of some thermodynamic parameters on system performance were examined. A parametric optimization was performed to obtain the optimum system performance. Hanbury and Vasquez (2018) were performed a life cycle analysis of geothermal energy for power and transportation with a stochastic approach. They showed that geothermal energy extraction is not without environmental cost. Aksoy (2014) was provided information on power generation via geothermal resources and sector development. He considered by a power plant at Kızıdere in Denizli, whereas the first private sector investment was the Dora-I power plant, commissioned in 2006. Koroneos *et al.* (2017) studied an exergy analysis for a proposed binary geothermal power plant in Nisyros Island, Greece. According to their study, a system exergetic efficiency of 41% and a thermal one of 12.8% has been resulted in supporting the technical feasibility of the proposed geothermal plant. Kolahi *et al.* (2018) were presented a novel approach for optimizing and also improving a flash binary geothermal power plant. They have shown an investigation on flash chamber pressure effect on the system performance was accomplished. Shokati *et al.* (2015) were compared a basic, dual-pressure, and dual-fluid ORCs and Kalina cycle for power generation from the geothermal fluid reservoir from energy, exergy, and exergoeconomic viewpoints. Heberle *et al.* (2017) were investigated a techno-economic analysis of a solar thermal retrofit for an air-cooled geothermal Organic Rankine Cycle power plant. Their analysis results indicated that the detailed simulations throughout one year show up to 7.8% more electricity, a solar-to-electric efficiency of 10% and a significant power gain during summer. Unverdi and Cerci (2013) were performed a performance analysis of Germencik Geothermal Power

Plant. They calculated the second law efficiency of overall plant has been found to be 35.34%. The study results were given in tables and the largest loss of exergy was determined to occur in separators. Zare (2015) investigated and compared the performance of three organic Rankine cycles (ORC) for binary geothermal plants and evaluated three ORC configurations that considered product cost optimization and proper model selection for the plants. Bina *et al.* (2018) were evaluated an exergoeconomic analysis and optimization of single and double flash cycles for Sabalan geothermal power plant. Their evaluation of the plant showed that in double flash energy and exergy efficiency were increased from 16.26% and 40.06% to 17.73% and 50.89%, respectively. Rachmat *et al.* (2018) were conducted an exergoeconomic analysis and optimization of a combined double flash binary cycle for Ulubelu geothermal power plant in Indonesia. The proposed system was used current data and properties of brine exploited from the Ulubelu geothermal well in Indonesia and four working fluid candidates, namely n-Pentane, R141b, R123, and R245fa are used in binary cycles. The results showed that n-pentane is the best working fluid where optimization indicated that the system can be generated 63.5 MW electricity with thermal and exergy efficiencies of 17.6% and 65.2% and a specific cost of 1.70 \$/GJ, respectively.

The study presents an exergoeconomic performance evaluation of an existing Afyon Geothermal Power Plant. Exergoeconomic approach was developed and used to determine the optimum working conditions in the plant. In this context, an exergoeconomic performance analysis of the plant was performed. As can be seen in the open literature, there is no thermodynamic and economic analysis for the plant. A detailed thermodynamic and exergoeconomic analyses of this plant has not been done before in the current status of the literature. Therefore this study is almost original and new for this plant. The novelty of the study is performance analysis of the existing plant, which is currently installed and operating. The plant is performed the economics of thermodynamically modeled in a computer environment using exergoeconomic cost method in a comprehensive way for the use of geothermal energy in power generation. This study was performed by (1) thermodynamic analysis under current working conditions of the plant, (2) conducting exergy and exergetic cost analyses for each component of the plant and (3) the optimum working conditions and costs concerning the exergoeconomic analysis.

2. PLANT DESCRIPTION AND OPERATION CHARACTERISTICS

Only a fraction of geothermal resources have relatively high temperatures making them suitable for electricity production. Geothermal power plants have been in operation for decades in many parts of the world. Figure 1 shows the general overview of Afyon Geothermal Power Plant. It is an existing geothermal plant located at 10 km north side of the city center of Afyonkarahisar in western of Turkey. Geothermal liquid water at 110°C is extracted from two resource wells (AF-23 and R-260) at a rate of 150 kg/s. The production wells AF-23 and R-260, built between 2012 and 2014, are 800 m and 1800 m in depth, respectively. Opened on 13 July 2017, the plant started to produce electricity on 16 August 2017. This water is pumped to the energy conversion heat exchanger of the thermodynamic cycle. The installed capacity of Afyon geothermal power plant located in Afyonkarahisar is 2.76 MW and it provides energy requirements of an average 4762 dwellings. A natural landscape of the Omer Gecek binary geothermal power plant is given in Fig. 1. The plant consists of three parts. These are the cycle of the geothermal water, the cycle of the ORC (R134a), and the cycle of cooling water. In order to convert the vapor form of R134a that reaches high pressure with the cooling water cycle to the geothermal water at the turbine outlet, the working fluid is supplied to the condenser at the correct flow and temperature, and it is necessary for efficient energy conversion of geothermal water. For this reason, when the average monthly air temperatures in Afyonkarahisar province are examined, it will help us to predict the cooling fluid temperature and performance graphs regarding the approach to the design values of cooling water. The plant modeling and SCADE view are given below in Fig. 1.

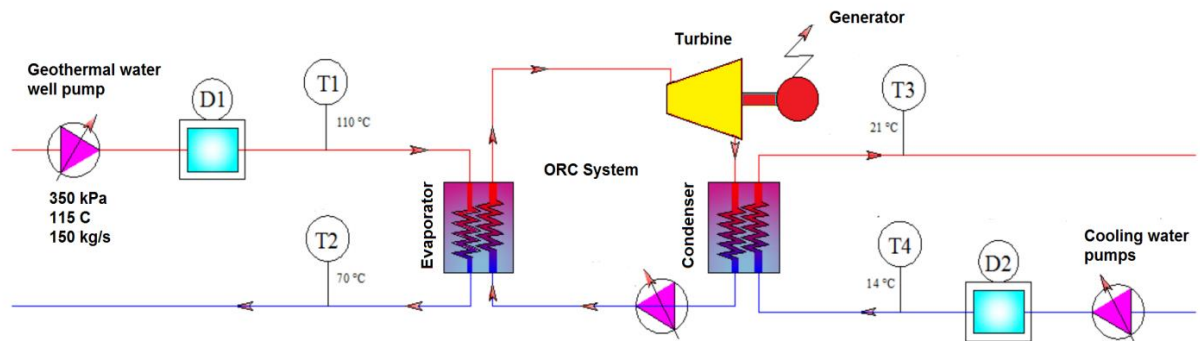


Figure 1. Afyon Geothermal Power Plant SCADA view (Sahin, 2016).

3. PLANT WORKING PRINCIPLE

Different thermodynamic cycles can be used for producing power from geothermal resources. The readers are referred to Kanoglu (2002) for a detailed coverage of geothermal power plants. A case study on an existing binary geothermal power plant is available in this study. Binary cycle plants use the geothermal brine from liquid-dominated resources at relatively low temperatures. The binary plant in Afyonkarahisar uses a geothermal resource at 110°C (Sahin, 2016). These plants operate on a Rankine cycle with a binary working fluid that has a low boiling temperature. The working fluid is completely vaporized and usually superheated by the geothermal water in a heat exchanger network, as shown in Fig. 2. In this configuration, the resulting vapor expands in the turbine, and then condenses in an air-cooled condenser (dry cooling tower) before being pumped back to the heat exchangers to complete the cycle. Fig. 2 shows the water cooled binary geothermal cycle. R134a was assumed for the working fluid which is the most efficient working fluid in the low-temperature binary cycle power plants. The thermodynamic details of the working fluid selection are given in comparison to the results and discussion section. The vaporized working fluid is expanded through a binary turbine to generate electricity. The expanded working fluid in the turbine is subsequently condensed in a water cooler and returned to the heat exchangers to be heated by hot geothermal water again. Generally, an air-cooled condenser is used, but water-cooled condenser is used in this plant. The reason for this is that it is a river basin suitable for cooling near the power plant. Therefore, more efficient cooling can be achieved. The geothermal water is often reinjected into the reservoir via the reinjection well. When the binary cycle is used in the geothermal power plants are insensitive to the presence of non-condensable gases and produce nearly no environmental emissions. The binary geothermal power plant is a heat engine that converts energy in geothermal water into shaft work of turbine, usually made available on a steam turbine shaft. The Afyon geothermal plant uses geothermal water at 110°C as the heat source of the binary cycle (Sahin, 2016).

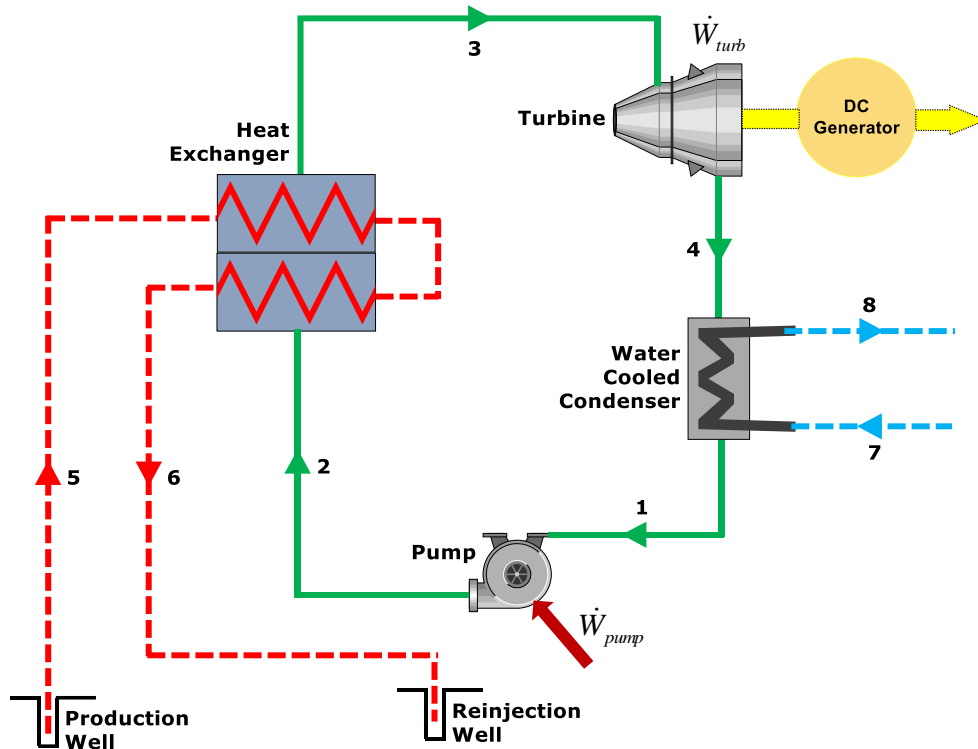


Figure 2. Simplified schematic configuration of Afyon Geothermal Power Plant.

4. THERMODYNAMIC MODELING

Afyon Binary Geothermal Power Plant operates on a steady state and steady flow condition. For thermodynamic analysis, we use properties of water for geothermal water. Control volume has been conserved mass, energy, entropy, and exergy. The equation equilibriums for the plant are as follows (Abusoglu and Kanoglu, 2008).

$$\sum m_i = \sum \dot{m}_e \quad (1)$$

$$\dot{Q} + \dot{W} = \sum \dot{m}_e h_e - \sum \dot{m}_i h_i \quad (2)$$

$$\sum \frac{\dot{Q}}{T_s} + \dot{S}_{gen} = \sum \dot{m}_e s_e - \sum \dot{m}_i s_i \quad (3)$$

$$\dot{E}x_{heat} - \dot{W} = \sum \dot{m}_e ex_e - \sum \dot{m}_i ex_i + \dot{E}x_{dest} \quad (4)$$

where ex is the specific flow exergy, \dot{W} and \dot{Q} are the net work and heat transfer, the mass flow rate is denoted by \dot{m} , enthalpy is represented by h , $\dot{E}x_{dest}$ is the amount of exergy destruction and $\dot{E}x_{heat}$ is the amount of exergy transfer by heat. Although we will select real operation values for the geothermal water and the cycle parameters, the results will be almost realistic. Here are assumed parameters: geothermal water temperature, $T_5 = 110^\circ\text{C}$. Geothermal water mass flow rate, $\dot{m}_{geo} = 150 \text{ kg/s}$. Dead state temperature, $T_0 = 14^\circ\text{C}$. Optimum flash process pressure, $P_5 = 143.4 \text{ kPa}$. Binary turbine inlet pressure, $P_3 = 2800 \text{ kPa}$. Turbine isentropic efficiencies, $\eta_{turb} = 90\%$. Analysis environment dead state pressure, $P_0 = 89.4 \text{ kPa}$, respectively. Mass, energy and exergy balance equations applied to the all components are expressed in the Table 1, according to the above thermodynamic considerations and assumptions.

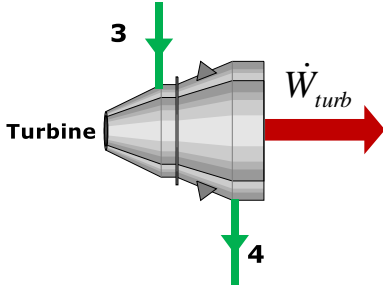
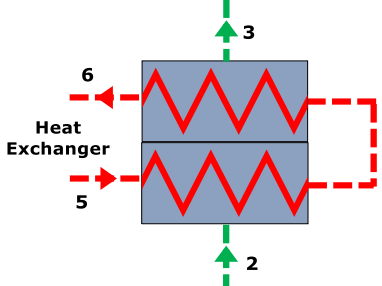
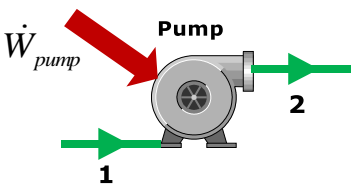
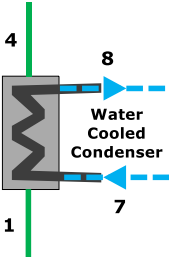
The energy efficiency of the binary geothermal power plant can be written according to the above equations as:

$$\eta = \frac{\dot{W}_{net,geo}}{\dot{E}_{geo}} = \frac{\dot{W}_{net,binary} - \dot{W}_{parasitic}}{\dot{m}_{geo}(h_{geo} - h_0)} \quad (5)$$

The exergy efficiency of the combined geothermal power plant can be written using exergy of the geothermal water at well head as:

$$\varepsilon = \frac{\dot{W}_{net,geo}}{\dot{E}x_{geo}} = \frac{\dot{W}_{net,binary} - \dot{W}_{parasitic}}{\dot{m}_{geo}(h_{geo} - h_0 - T_0(s_{geo} - s_0))} \quad (6)$$

Table 1. Thermodynamic balance equations applied to the all system components.

System component	Mass, energy and exergy equations
 <p>Turbine</p>	$\dot{m}_3 = \dot{m}_4$ $\dot{W}_{turb,act} = \dot{m}_3(h_3 - h_4)$ $\dot{W}_{turb,rev} = \dot{m}_3(ex_3 - ex_4)$ $\dot{E}x_{turb,dest} = \dot{W}_{turb,rev} - \dot{W}_{turb,act}$ $\varepsilon = \frac{\dot{W}_{turb,act}}{\dot{W}_{turb,rev}}, \eta_{turb} = \frac{h_3 - h_4}{h_3 - h_{4s}}$
 <p>Heat Exchanger</p>	$\dot{m}_3 = \dot{m}_2, \dot{m}_6 = \dot{m}_5$ $\dot{m}_2(h_3 - h_2) = \dot{m}_5(h_5 - h_6)$ $\dot{E}x_{BHE,dest} = \dot{m}_5(ex_5 - ex_6) - \dot{m}_2(ex_3 - ex_2)$ $\varepsilon = \frac{\dot{m}_2(ex_3 - ex_2)}{\dot{m}_5(ex_5 - ex_6)}$
 <p>Pump</p>	$\dot{m}_2 = \dot{m}_1$ $\dot{W}_{pump,act} = \dot{m}_2(h_2 - h_1)$ $\dot{W}_{pump,rev} = \dot{m}_2(ex_2 - ex_1), \varepsilon = \frac{\dot{W}_{pump,rev}}{\dot{W}_{pump,act}}$ $\dot{E}x_{pump,dest} = \dot{W}_{turb,act} - \dot{W}_{turb,rev}$
 <p>Water Cooled Condenser</p>	$\dot{m}_4 = \dot{m}_1, \dot{m}_8 = \dot{m}_7$ $\dot{m}_4(h_4 - h_1) = \dot{m}_7(h_8 - h_7)$ $\dot{E}x_{WCC,dest} = \dot{m}_4(ex_4 - ex_1) - \dot{m}_7(ex_8 - ex_7)$ $\varepsilon = \frac{\dot{m}_7(ex_8 - ex_7)}{\dot{m}_4(ex_4 - ex_1)}$

Binary heat exchanger pinch analysis is performed as the design consideration of the binary plant. The power consumption to the production and pumps is usually small compared to the turbine power. However, the power consumed by the cooling fans in the condenser can be up to 20% of the turbine power (Kanoglu and Dincer, 2009). Energy and exergy characteristics for each state of the system in Fig. 2 are calculated in Table 2. The thermodynamic properties of the liquid and gaseous phases of the geothermal water and of the selected working fluid of R134a in the binary cycle are calculated by computer software program EES (F-Chart Software, 2015). The thermodynamic analysis is critical because it forms the basis of exergoeconomic analysis. For this reason, the thermodynamic analysis must be done correctly. In Table 2, exergy values of all states in the plant are calculated and are given in detail. These values are calculated taking into account the actual operating conditions of the plant as mentioned before.

Table 2. Plant thermodynamic performance analysis results.

State	Fluid	P (kPa)	T (°C)	\dot{m} (kg/s)	h (kJ/kg)	s (kJ/kg°C)	ex (kJ/kg)	$\dot{E}x$ (kW)
0	Geothermal	89.4	11.3	-	47.56	0.1703	-	-
0'	R-134a	89.4	11.3	-	265.1	1.076	-	-
0''	Water	89.4	11.3	-	47.52	0.1701	-	-
1	R-134a	1650	15.7	108	73.33	0.2802	34.54	3731
2	R-134a	120	17.0	108	75.51	0.2814	36.39	3931
3	R-134a	120	100	108	309	0.9644	75.74	8182
4	R-134a	1650	34.1	108	276.9	0.9831	38.29	4137
5	Geothermal	1650	110	150	461.4	1.419	58.9	8835
6	Geothermal	720	70	150	293.1	0.9552	22.38	3357
7	Water	100	11.3	541.9	47.52	0.1701	0	0
8	Water	100	21	541.9	88.1	0.3104	0.6976	378

5. EXERGOECONOMIC MODELING

Exergoeconomic analysis is a highly realistic method of assessing the cost of a thermal system that inevitably interacts with the environment. Since the available thermodynamic values of mass, heat, and work in the systems can be determined by exergy, it is significant that the exergy is used when cost allocation is made in thermal systems. We refer to this approach as exergy costing. Thus, the cost of power and heat flow associated with exergy entering and leaving the system can be expressed by the following equations. The purchase equipment costs and the operating maintenance costs of the plant equipment are considered as the fundamental part of the system costs. These two main cost parameters include all other cost parameters of the plant. Thus, the cost balance for system equipment can be written as (Bejanet *al.*, 1996):

$$\sum_{in} \dot{C}_{k,in} + \dot{Z}_k^T + \dot{C}_k^Q = \sum_{out} \dot{C}_{k,out} + \dot{C}_k^W \quad (7)$$

Here

$$\dot{C} = c \times \dot{E}x \quad (8)$$

For any k component, the exergy rates of inlet and exit are calculated by using exergy relations. \dot{Z}_k^T is the cost ratio for a component in \$/h. The general equation of the cost ratio associated with initial cost and operating-maintenance costs for a component can be expressed as (Bejanet *al.*, 1996):

$$\dot{Z}_k^T = \dot{Z}_k^{IC} + \dot{Z}_k^{OMC} \quad (9)$$

The economic analysis results of the power plant and equipments with Aspen Plus program in the computer environment are given in Table 3.

Table 3. The cost rates associated with the components of the plant (F-Chart Software, 2015; Aspen Plus, 2015).

Components	PEC (\$)	\dot{Z}_k^{IC} (\$/h)	\dot{Z}_k^{OMC} (\$/h)	\dot{Z}_k^T (\$/h)
Binary Heat Exchanger	300,000	4.233	3.488	7.722
Binary Turbine	750,000	10.584	8.722	19.306
Water cooled condenser	300,000	4.233	3.488	7.722
Binary pump	100,000	1.411	1.162	2.574
Other system outlays	100,000	1.411	1.162	2.574
Total purchase equipment cost (PEC)	1,550,000	21.872	18.022	39.894
Operating and maintenance cost (OMC)	150,000			

6. EXERGOECONOMIC COST RELATIONS

The cost of power and heat flow associated with exergy entering and leaving the system can be expressed by the following equations. Exergoeconomic cost balance equations can be expressed as (Bejan *et al.*, 1996):

$$\dot{C}_i = c_i \dot{E}x_i = c_i (\dot{m}_i e_i) \quad (10)$$

$$\dot{C}_e = c_e \dot{E}x_e = c_e (\dot{m}_e e_e) \quad (11)$$

$$\dot{C}_w = c_w \dot{W} \quad (12)$$

$$\dot{C}_q = c_q \dot{E}x_q \quad (13)$$

From here, the exergetic cost balance due to the heat generated and power for a system component can be written as:

$$\sum_e (c_e \dot{E}x_e)_k + c_{w,k} \dot{W}_k = c_{q,k} \dot{E}x_{q,k} + \sum_i (c_i \dot{E}x_i)_k + \dot{Z}_k^T + \sum_i (c_i \dot{E}x_i) \quad (14)$$

The above equation states that the total cost of the exergy flow from the system for a system component is equal to all the expenditure required to calculate this cost: the cost of the incoming exergy flow plus the initial investment and other costs. All equipment of the plant exergy costing are expressed as in Table 4.

Table 4. Cost balance equations and auxiliary equations of the system.

Component	Exergetic cost rate balance equation	Auxiliary Equations
Binary Heat Exchanger	$\dot{C}_5 + \dot{C}_2 + \dot{Z}_{BHE} = \dot{C}_6 + \dot{C}_3$	$c_5 = c_6$ c_3 (variable)
Binary Turbine	$\dot{C}_3 + \dot{Z}_{BT} = \dot{C}_{WT} + \dot{C}_4$	$c_3 = c_4$ $c_{electricity}$ (variable)
Water cooled condenser	$\dot{C}_4 + \dot{C}_7 + \dot{Z}_{WCC} = \dot{C}_8 + \dot{C}_1$	$c_8 = c_7$ $c_7 = 0$
Binary pump	$\dot{C}_1 + \dot{C}_{Wp} + \dot{Z}_{BP} = \dot{C}_2$	c_1 (known) c_2 (variable)

7. RESULTS AND DISCUSSION

7.1. Thermodynamic Analysis

As a result of the thermodynamic analysis, the energy efficiency of the Afyon Geothermal binary power plant was calculated as 10.4% based on the energy input to the R134a binary cycles, according to the states at 7 and 8. Approximately 90% of the geothermal water energy in the reservoir means that it cannot be used and is rejected as heat or reinjected back to the ground. The exergy rate input the plant was calculated as 8835 kW by approaching the approximate value of the exergy transferred from the geothermal water to the binary plant supported by the secondary working fluid (R134a). The net power production from the binary plant was calculated as 2622 kW. The exergy change of geothermal water is thought to be the additional exergy input to the cycle in the well state. According to these conditions, the exergy efficiency of the dual geothermal power plant was calculated to be 29.7%.

The exergy rates and distributions of the components exergy destruction of the Afyon Geothermal Power Plant is given in Figures 3 and 4. After using in the plant, geothermal water is reinjected into the underground. The geothermal water reinjection exergy loss of geothermal water is calculated to be 3357 kW. In geothermal power plants, reinjection is the most loss of exergy destruction. The large part of the energy from the geothermal water is rejected from the plant without being used. The most destructive components are the binary heat exchanger and turbine, representing 1227 kW and 572.6 kW of the total exergy destruction. This power plant is used Akarçay river water as cooling water in the condenser unit (Sahin, 2016).

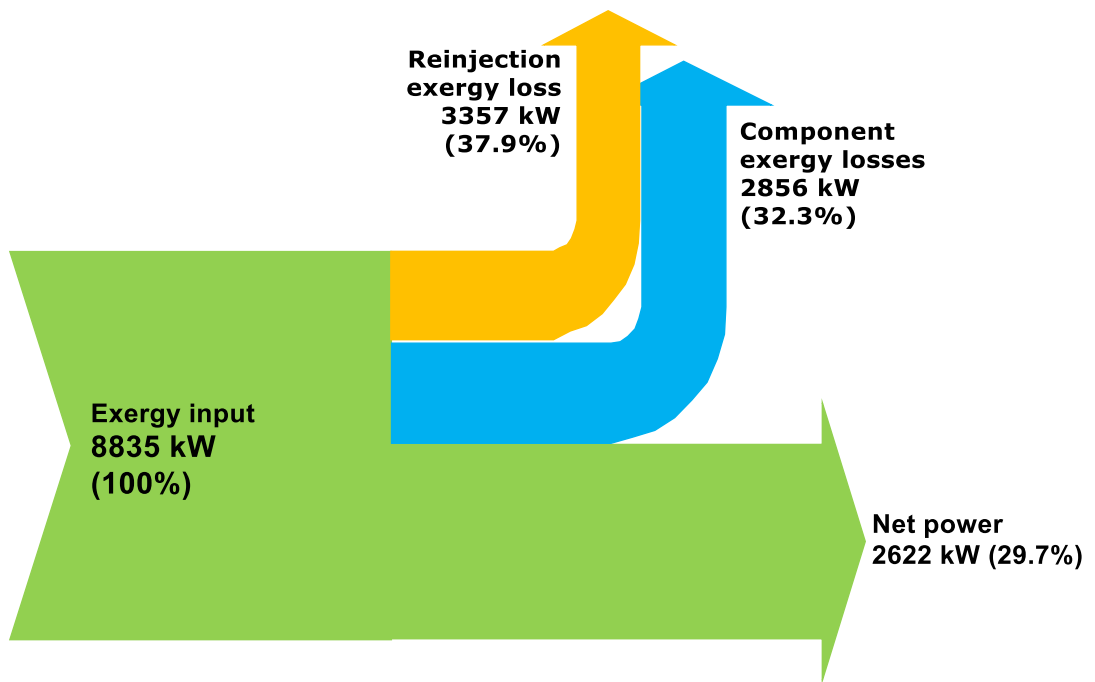


Figure 3. Exergy flow diagram of Afyon Geothermal Power Plant.

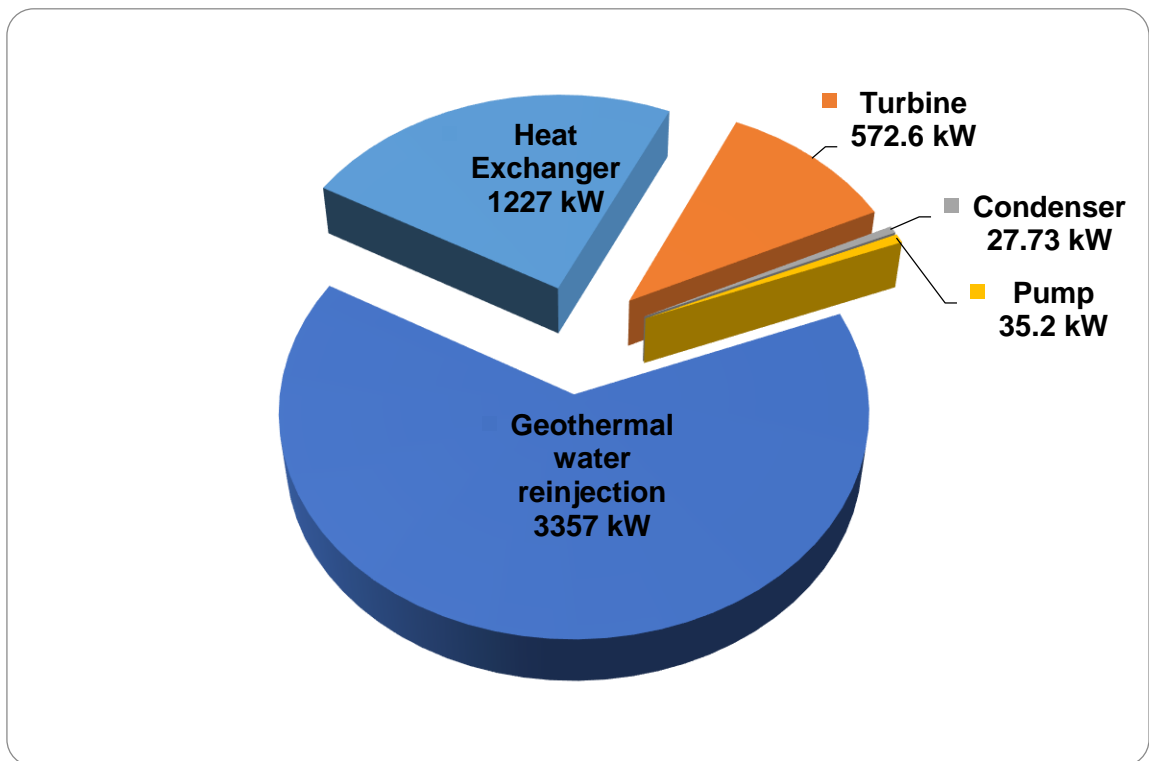


Figure 4. Exergy destructions in the components of the plant.

7.2. Exergoeconomic analysis

The total purchase and equipment costs and exergetic cost rates of the plant components are given in Table 3. The unit cost of the geothermal water as a fuel input to the plant is calculated to be 1.372 \$/GJ and the exergetic cost of binary working fluid R134a is 3 \$/kg and the exergetic cost of the working fluid R134a is calculated to be 2.86 \$/GJ (Ergun *et al.*, 2017). According to the exergoeconomic method, a sufficient number of auxiliary equations have been developed with the help of Fuel and Product principles for the system components and the cost equilibrium equations related to these equations are given in Table 4. The results in Table 5 are obtained when the exergy cost equations are written in the EES program and simultaneously solved in the computer environment. From this analysis, the exergy cost ratio of the R134a working fluid is evaluated to be 49.7 \$/h at the exit state of the binary system pump. The unit exergy cost of the produced electricity by making technical assumptions and solving with auxiliary equations from the plant is calculated to be 6.47 \$/GJ or 0.0233 \$/kWh, respectively.

Table 5. Exergoeconomic results of the plant.

State	\dot{E}_x (kW)	C (\$/GJ)	\dot{C} (\$/h)
1	3731	3.099	41.62
2	3931	3.51	49.68
3	8182	2.867	84.46
4	4137	2.867	42.7
5	8835	1.372	43.64
6	3357	1.372	16.58
7	0	6.47	0
8	378	6.47	8.803
$\dot{W}_{Turbine}$	3473	6.47	80.88
\dot{W}_{Pump}	235.6	6.47	5.486
$\dot{W}_{Parasitic}^2$	615.1	6.47	14.32
\dot{W}_{Plant}	2622	6.47	61.07

Fig.5 shows the exergy cost destruction under real operating conditions for the plant components. The binary heat exchanger is the higher exergy cost destructive component compared to the other plant components. The way of the reducing the cost of electricity generated in the power plant is to reduce the exergy cost destruction of the plant. It is also considered to increase plant efficiency, to reduce exergy losses and to optimize operating conditions of the plant.

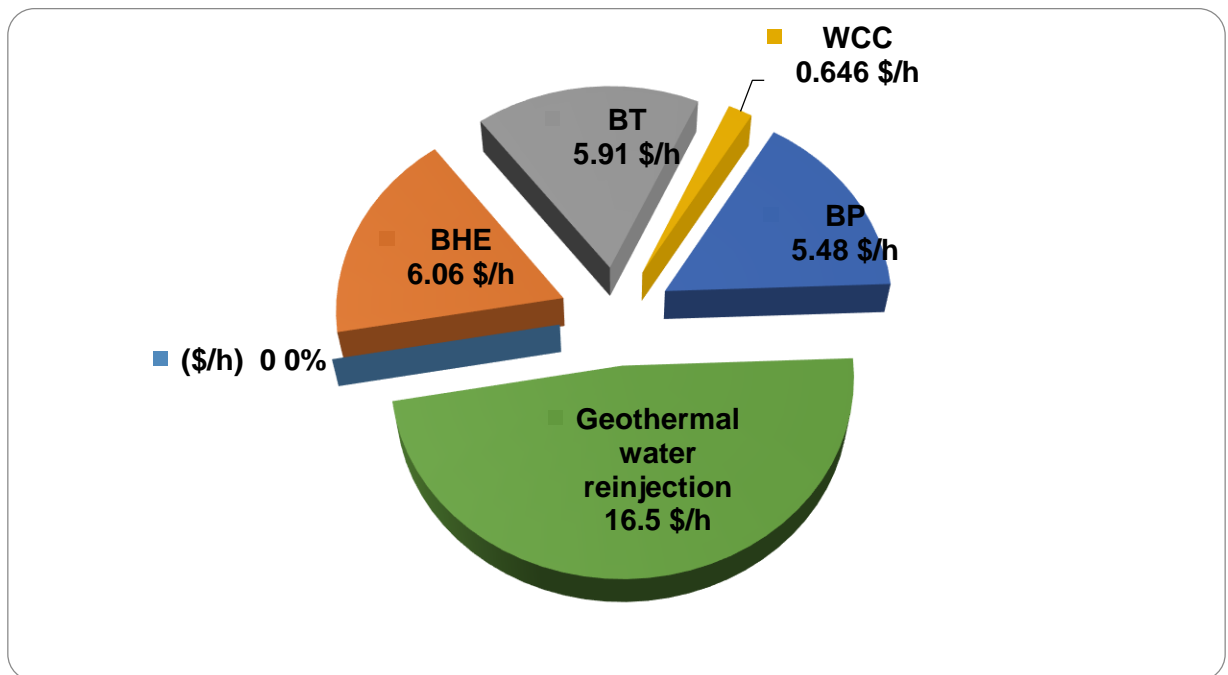


Figure 5. Distrubution of exergetic cost destruction rate diagram of the plant.

In this section, we also investigated how the results changed if different working fluids are used. Currently, installed plant is started with R134a binary fluid and we have also investigated for the most commonly used working fluids, Isobutane and n pentane. Some basic results of the plant are given in Table 6. The results are obtained for the same value of the working conditions in the plant as $T_{geo,in} = 110^{\circ}\text{C}$ and $T_{geo,out} = 70^{\circ}\text{C}$. Different working fluids cost comparisons of electricity production from the plant are evaluated in Table 6. At the same time, this comparison shows the optimum working fluid selection for the binary geothermal plant according to the operating conditions of the plant. The optimization is showed that R134a is caused to be the most efficient power production, and also has the lowest cost of the electricity production from the plant. The difference in the production costs evaluated with R134a and Isobutane is about 4.9%. The difference between the R134a and n-pentane working fluids is about 65.4%, whereas the difference between the Isobutane and n-pentane as to be used working fluid is about 63.6%.

Table 6. Different working fluids cost comparisons of electricity production.

Fluids	\dot{W}_{net} (kW)	η (%)	ε (%)	$C_{electricity}$ (\$/kWh)
R134a	2622	10.4	29.7	0.0233
Isobutane	2351	9.3	26.6	0.0245
n-pentane	1170	4.6	13.24	0.0674

Table 7 illustrates the use of the exergoeconomic variables introduced thus far for the evaluation of the geothermal plant. First, the design evaluation of the plant is presented, and then the performance evaluation of an existing plant is described. When applying the exergoeconomic methodology, recognize that the values of all exergoeconomic variables depend on the components (binary heat exchanger, turbine, pump, water-cooled condenser). The accompanying Table 7 summarizes the exergoeconomic parameters calculated for each component of the binary geothermal power plant using data from Fig. 2., and definitions from Tables 4 and 5.

Table 7. Exergoeconomic performance analysis results of the plant.

Components	$\dot{E}x_F$ (kW)	$\dot{E}x_P$ (kW)	$\dot{E}x_D$ (kW)	y^* (%)	ε (%)	$c_{F,k}$ (\$/GJ)	$c_{P,k}$ (\$/GJ)	\dot{C}_D (\$/h)
Binary heat exchanger	5478	4251	1227	23.5	77.6	1.372	2.867	6.06
Binary turbine	4045	3473	572.6	10.9	85.8	2.867	6.470	5.91
Water cooled condenser	405.7	378	27.73	0.5	93.1	6.469	3.099	0.646
Binary pump	235.6	200.4	35.2	0.67	85.0	6.469	3.510	5.486
Geothermal water reinjection	8835	2622	3357	-	-	-	-	16.58
Overall System	10,164	8302	5219	35.7	81.6	1.372	6.470	13.44

7.3. Parametric analysis of the plant

In the system, the unit kJ is the amount of energy generated from the geothermal water. In the system, the amount of unit kJ energy is increased with increasing geothermal water temperature from the unit kg of geothermal water. In this context, parametric studies have been performed to observe how some critical parameters of the system variation with the temperature of the geothermal source. In particular, the power obtained from the plant and the exergy cost of electricity generated by the geothermal water temperature was investigated. The power generation from the plant increases almost linearly with the geothermal water temperature as shown in Fig. 6. The parametric study showing the power output was performed at temperatures between 100 and 150°C. Fig. 6 shows that the geothermal water temperature directly affects the net power output of the system. The net power production from the plant increased from 2622 kW at 110°C to 6633 kW at 150°C, respectively.

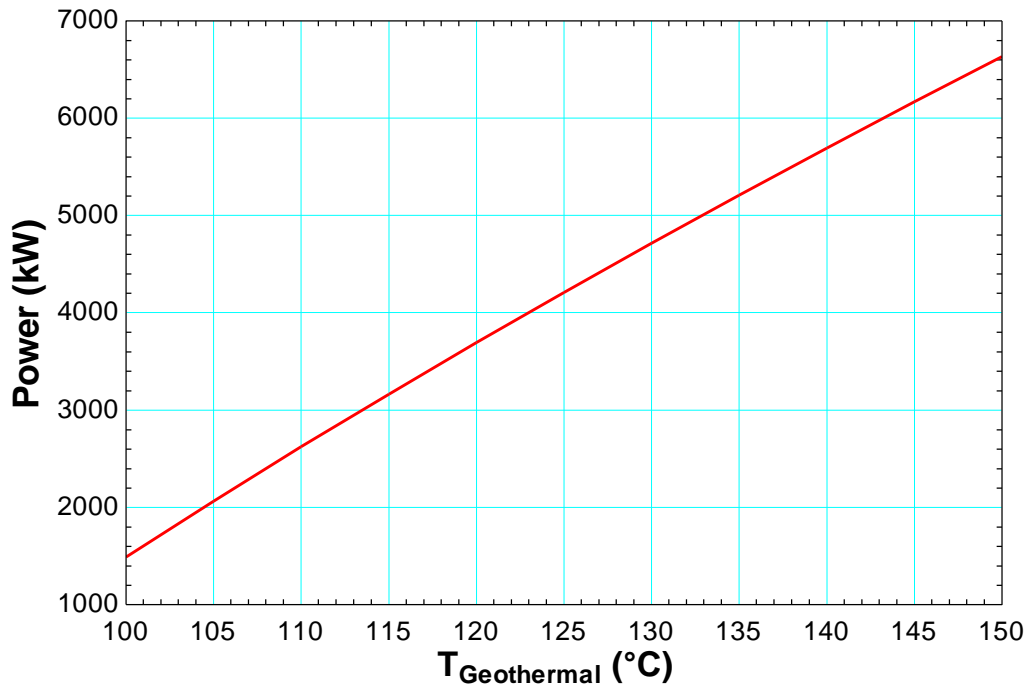


Figure 6. Power production of plant with geothermal water temperature.

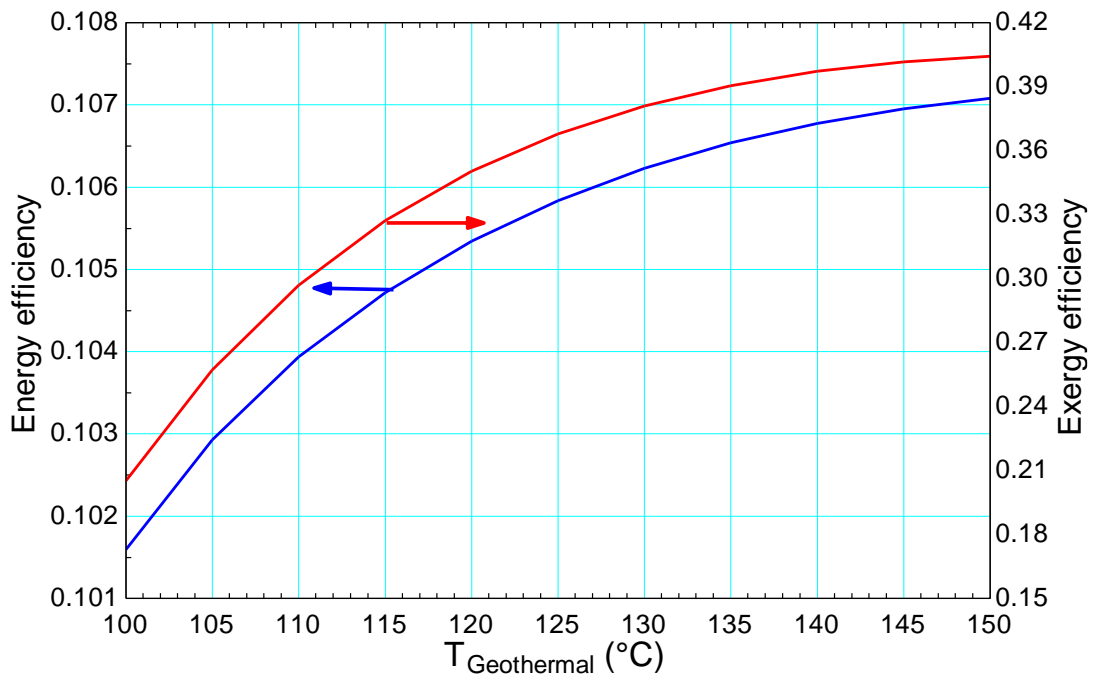


Figure 7. Thermodynamic performance evaluation of the plant.

The variation of electricity cost concerning the geothermal water temperature is shown in Fig. 8. The unit exergetic cost of electricity decreases with the geothermal temperature increases. In the current working condition of the plant, the unit exergetic cost of electricity is 0.0233 \$/kWh at 110°C.

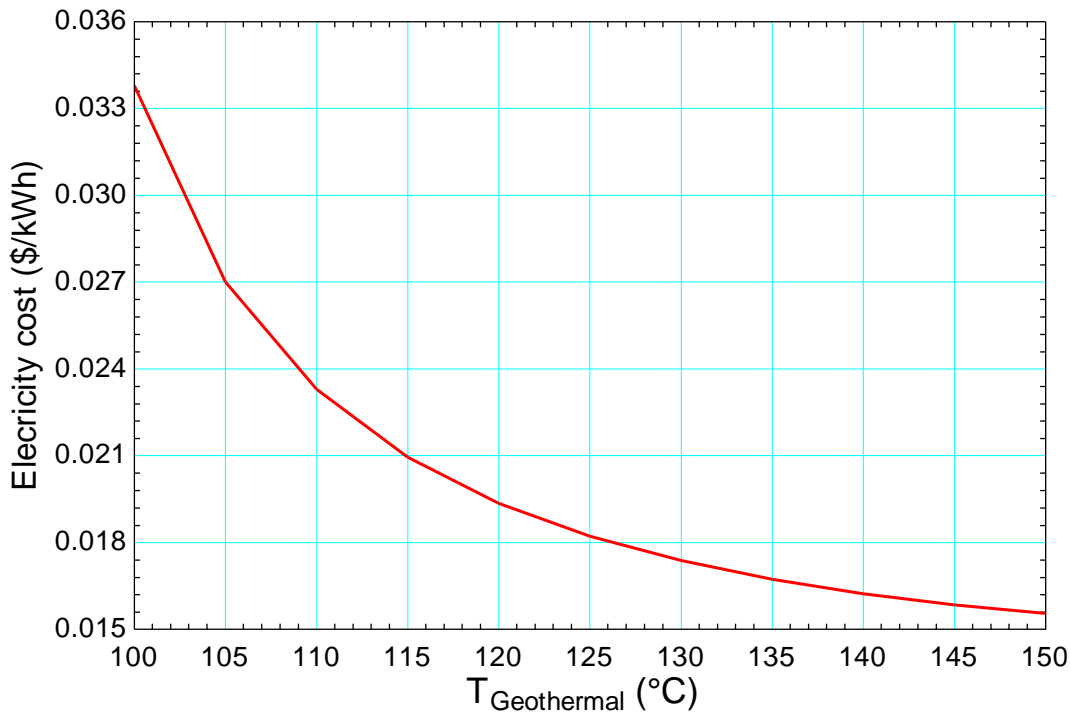


Figure 8. Electricity cost with geothermal water temperature.

8. CONCLUSIONS

The generating electricity using binary cycle by the direct or indirect heating method according to geothermal source temperature and capacity is a more advantageous and profitable investment compared to district heating. Therefore, this study will guide the determination of optimum power plant installed capacity in low temperature and capacity geothermal fields. Thermophysical properties of the working fluids (geothermal water, water, isobutene and air) are obtained from EES software with built-in thermodynamic property functions. In this study, the performance evaluation of the geothermal power plant, which became operational in Afyonkarahisar province in July 2017, was performed by using actual plant data. The optimum operating conditions of the system and the optimum value of the electricity cost were investigated. In this context, the study has been presented to the authorities, and it has been an innovative and useful research to increase the feasibility and energy efficiency of the existing plant. Some important results obtained are summarized from the plant as follows:

- Energy and exergy values inputs from the geothermal water are evaluated with the base assumptions to be 62,079 kW and 8835 kW, respectively.
- The plant, the exergy input by the power plant is 8835 kW and the rate of heat rejection is to be determined as 6213 kW and this value correspond to 29.7 % of totally exergy input by the geothermal water.
- The energy and exergy efficiencies were evaluated as 10.4 % and 29.7 % for Afyon Geothermal Power Plant (AFJES).
- The unit exergy cost of the produced electricity by making technical assumptions and solving with auxiliary equations from the plant is calculated to be 0.0233 \$/kWh, respectively.

9. NOMENCLATURES

- β geothermal water specific energy consumption, kg/kJ
 c specific exergy cost, \$/kJ

C	cost associated with exergy flow, \$
\dot{C}	cost rate associated with exergy, \$/h
$\dot{E}x$	exergy rate, kW
ex	specific exergy, kJ/kg
h	enthalpy, kJ/kg
\dot{m}	mass flow rate, kg/s
PEC	purchased equipment cost, \$
s	entropy, kJ/kg K
T	temperature, °C
\dot{W}	power, kW
\dot{Z}	equipment cost rate, \$/h

Greek symbols

η	energy efficiency
ε	exergy efficiency
\$	United State Dollars, US\$

Subscripts

0	dead states
act	actual
BHE	binary heat exchanger
BT	binary turbine
dest	exergy destruction
e	exit state
$elec$	electricity
F	exergy of fuel
geo	geothermal
IC	investment cost
i	inlet state
k	k-th equipment
P	exergy of product
rev	reversible
turb	turbine
T	total
WCC	water cooled condenser

Superscripts

- time rate
- IC investment cost
- OMC operation maintenance

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