Isı Bilimi ve Tekniği Dergisi, 40, 1, 37-51, 2020
J. of Thermal Science and Technology

ISSN 1300-3615

IMPROVING PERFORMANCE AND THERMOECONOMIC OPTIMIZATION OF AN EXISTING BINARY GEOTHERMAL POWER PLANT: A CASE STUDY

Ceyhun YILMAZ*
*Afyon Kocatepe Üniversitesi Teknoloji Fakültesi Makina Mühendisliği Bölümü
03200 Merkez, Afyonkarahisar, ceyhunyilmaz@aku.edu.tr

(Geliş Tarihi: 05.02.2019, Kabul Tarihi: 16.01.2020)

Abstract: Geothermal power plants have been in operation for decades in many parts of the world. Different thermodynamic cycles can be used for producing power from geothermal resources. Binary cycle plants use the geothermal water from liquid-dominated resources at relatively low temperatures. These plants operate on a Rankine cycle with a binary working fluid (isobutane, pentane, isopentane, R-114, etc.) that has a low boiling temperature. A case study on an existing binary geothermal power plant is available in this study. Thermoeconomic performance evaluation and optimization of 2.7 MW binary organic Rankine cycle (ORC) design geothermal power plant in western Turkey is conducted using actual plant operating data, and potential improvements are identified. Afyon Geothermal Power Plant (AFJES) is thermodynamically modeled in a computer environment using current working parameters in a comprehensive way for the use of geothermal energy in electricity generation. 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 with a simple payback period of 3.36 years. The exergetic cost of the electricity from the plant is calculated as 0.0233 $/kWh. The optimized simple payback period and exergy cost of the electricity generated in the plant is calculated as 2.87 years and 0.0176 $/kWh, respectively.
Keywords: Geothermal power plant, thermodynamic analysis, thermoeconomic analysis, optimization.

MEVCUT BİR BİNARY JEOTERMAL SANTRALİN PERFORMANS GELİŞTİRMESİ VE TERMOEKONOMİK OPTİMİZASYONU: BİR VAKA ÇALIŞMASI

Özet: Jeotermal güç santralleri dünyanın birçok yerinde yıllardır kullanılmaktadır. Jeotermal kaynaklardan güç üretmek için farklı termodinamik çevrimler kullanılabilir. Binary çevrim santralleri, nispeten düşük sıcaklıklarda sıvı yoğunluklu kaynaklardan gelen jeotermal suyu kullanır. Bu santraller, düşük kaynama sıcaklığına sahip bir binary iş akışkanı (izobütan, pentan, izopentan, R-114, vb.) ile Rankin çevrimiyle çalışır. Bu çalışmada, mevcut bir binary jeotermal güç santrali ile ilgili bir vaka çalışması yapılmıştır. Türkiye'nin batısındaki 2.7 MW'lık Binary Organik Rankine çevrimi (ORC) tasarımı bir jeotermal santralin termoekonomik performans değerlendirmesi ve optimizasyonu, gerçek santral çalışma verileri kullanılarak yapılmış ve geliştirme potansiyeli tespit edilmiştir. Afyon Jeotermal Enerji Santrali (AFJES), elektrik üretiminde jeotermal enerjinin kullanımı için mevcut çalışma parametreleri kapsamlı bir şekilde kullanılarak bilgisayar ortamında termodinamik olarak modellenmiştir. Santralin jeotermal su sıcaklığı ve kütlesel debisi sırasıyla 110 °C ve 150 kg/s'dir. Santralin enerji ve ekserji verimliliği % 10.4 ve % 29.7 olarak hesaplanmıştır. Jeotermal elektrikten elde edilen gelir 2.880.277 $/yıl ve basit bir geri ödeme süresi ise 3.36 yıl olarak hesaplanmıştır. Santralden üretilen elektriğin ekserjetik maliyeti 0.0233 $/kWh olarak hesaplanmıştır. Santralden üretilen elektriğin optimize edilmiş basit geri ödeme süresi ve ekserji maliyeti sırasıyla 2.87 yıl ve 0.0176 $/kWh olarak hesaplanmıştır.
Anahtar Kelimler: Jeotermal güç santrali, termodinamik analiz, termoekonomik analiz, optimizasyon.

NOMENCLATURE

β	specific energy consumption, kg/kJ
c	specific exergy cost, $/kJ
C	cost associated with exergy flow, $
CRF	capital recovery factor
$\dot{C}$	cost rate associated with exergy, $/h
$\dot{E}x$	exergy rate, kW
ex	specific exergy, kJ/kg
f	exergoeconomic factor, %
h	enthalpy, kJ/kg
i	interest rate, %
$\dot{m}$	mass flow rate, kg/s
PEC	purchased equipment cost, $
PWF	present worth factor
r	relative cost difference, %
s	entropy, kJ/kg K
S	salvage value, $
SPP	simple payback period, year

t	time
T	temperature, °C
$\dot{W}$	power, kW
y	exergy destruction over total exergy destruction
$\dot{Z}$	equipment cost rate, $/h

Greek symbols

η	energy efficiency
ε	exergy efficiency
τ	capacity factor of system
$	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	fluid
F	exergy of fuel
geo	geothermal
IC	investment cost
i	inlet state
k	*k*-th equipment
pp	pinch point
P	exergy of product
rev	reversible
turb	turbine
T	total
WCC	water cooled condenser

Superscripts

•	time rate
CI	investment cost
OMC	operation maintenance
n	operating period, year

INTRODUCTION

Geothermal energy is within the earth's thermal energy that is transferred to the underground water. This thermal energy trapped beneath and within the earth. This energy exists in the form of steam and hot or liquid water. It is released naturally or drilling operations. The utilization of geothermal energy is not a new technology, as the first geothermal steam well was drilled at Larderallo, Italy, in 1904 (Kasaei et al., 2017). The present installed energy capacity of the plants is now around 1,144 MW, which has 40 power plants in Turkey (Balcilar et al., 2018). Turkey's geothermal resources mainly consist of low-grade energy sources. However, this is not a disadvantage because the recent progress of technological developments, Organic Rankine cycles (ORC) are preferred to produce electricity for low enthalpy type of geothermal sources. The most common cycle is the binary cycle that allows electricity generation from low-temperature geothermal energy sources (Yilmaz, 2017). The binary plants developed for the use of working fluids at low boiling points enable the generation of electricity from low-temperature geothermal water. Geothermal binary plant technology was developed primarily to produce electricity from low-temperature resources and to increase utilization of thermal resources by conversion waste heat (Korkmaz et al., 2014).

The binary plant at Chena Hot Springs uses a geothermal resource at 80ºC in Alaska (Zheng et al., 2015). The binary system uses a secondary working fluid, typically n-pentane, n-butane, and R144 which, compared with steam, have a low boiling point and high vapor pressure at low temperatures. This secondary fluid is operated through a conventional Rankine Cycle. By selecting the appropriate working fluid, binary plants can be designed to operate with inlet temperatures in the range 80 to 150°C. The upper-temperature limit is selected by the thermophysical condition of organic binary fluids. The lower temperature limit is primarily selected by useful and economic considerations, as the required heat exchanger size for a given capacity becomes impractical. Heat is transferred from geothermal water to the binary fluid via heat exchangers, where the binary fluid is heated and vaporized before being expanded through a turbine (Cengel and Boles, 2015).

In the open literature, some relevant studies have been conducted on geothermal energy for electricity production. Kanoglu (2002), 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), 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), 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), 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 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), 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 environ-mental cost. Aksoy (2014), provided an information on power generation via geothermal resources and sector development. He considered by a power plant at Kızıldere 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% have been resulted in supporting the technical feasibility of the proposed geothermal plant. Kolahi et al. (2018), 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), 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), investigated a technoeconomic 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. Coskun et al. (2014), considered a geothermal resource in Kutahya–Simav region in Turkey. Economic analysis of four cycles was considered to indicate that the cost of producing a unit amount of electricity is 0.0116 \$/kW h for double flash and Kalina cycles, 0.0165 \$/kW h for combined cycle, and 0.0202 \$/kW h for the binary cycle. Karimi and Mansouri (2018), presented a comparative profitability study of geothermal electricity production in developing countries. They are considered an exergoeconomic analysis and optimization of different cycle configurations. According to the results, the maximum and minimum values of the levelized cost of electricity are obtained as 0.1474 and 0.0493 \$/kWh, respectively. Kahraman et al. (2019), investigated the thermodynamic and thermoeconomic performances of a 21 MW geothermal plant. The results showed that ambient temperature affects efficiencies. The energy efficiency decreased from 13.7% to 9.2%, while exergy efficiency decreased from 54.9% to 36.7. The unit cost of products the plant increased from nearly 230 \$/GJ to 330 \$/GJ, respectively.

The study presents a thermoeconomic evaluation and optimization of an existing Afyon Geothermal Power Plant. Thermoeconomic approach was developed and used to determine the optimum working conditions in the plant. In this context, a thermoeconomic analysis of the plant was carried out, and the performance values were determined and optimized. As can be seen in the open literature, there is no thermodynamic and economic analysis for the plant. Thermodynamic and thermoeconomic analysis 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 an existing Afyon Geothermal Power Plant (AFJES), which is currently installed and operating. The plant is performed and optimized the economics of thermodynamically modeled in a computer environment using the thermoeconomic 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 thermoeconomic analysis. Moreover, the simple payback period of the current situation of the plant has been investigated with parametric studies for different working conditions.

EXISTING PLANT DESCRIPTION AND OPERATION

Figure 1 shows the general overview of Afyon Geothermal Power Plant (AFJES). 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 115ºC 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 wells are a liquid form of geothermal water resource at a relatively low temperature and a binary cycle is best suited for electricity power generation. 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 Afyon Geothermal Power Plant is given in Fig. 1 (Sahin, 2016).

Figure 1. A general overview of Afyon Geothermal Power Plant (AFJES) (Sahin, 2016).

The AFJES ORC 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. Afyon Geothermal Power Plant (AFJES) system modeling and SCADE view are given below in Fig. 2 (Sahin, 2016).

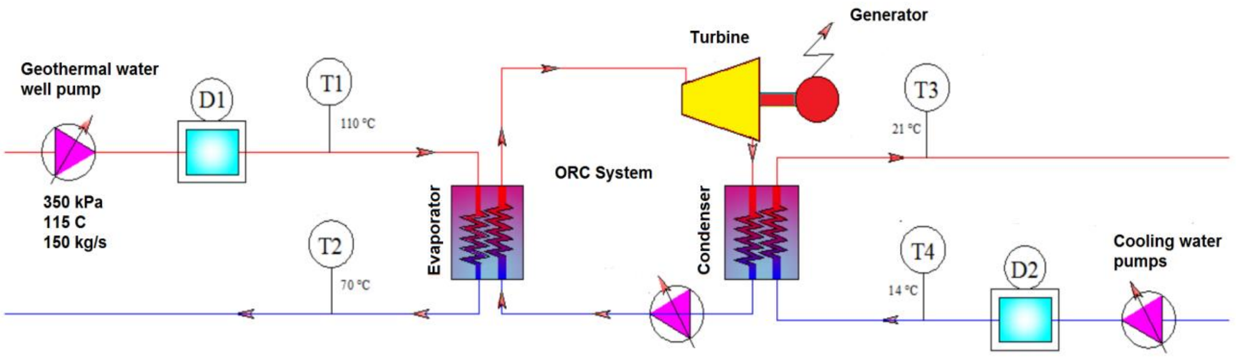


Figure 2. Afyon Geothermal Power Plant (AFJES) System Modeling and SCADA (Sahin, 2016).

WORKING PRINCIPLE OF PLANT

Fig. 3 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. Hot geothermal water passes through a series of heat exchangers, where the working fluid vaporizes. Then 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 110ºC as the heat source of the binary cycle. The plant has a power capacity of 2622 kW and operates on the simple Rankine cycle with R134a as the working fluid. Geothermal water energy is transferred to the binary cycle by a heat exchanger in which geothermal liquid water enters at 110ºC at a rate of 150 kg/s and leaves about at 70ºC. The geothermal water passes through a heat exchanger is reinjected into the ground about at 70ºC. Binary cycle working fluid of R134a enters the turbine 2800 kPa and 100ºC and leaves at 500 kPa. R-134a has condensed in a water-cooled condenser and pumped to the heat exchanger pressure. The isentropic efficiencies of the turbine and pump are assumed to be 85 percent. For the design of heat exchanger of the binary cycle is called pinch point temperature difference ΔT_{pp}. The value of ΔT_{pp} is usually taken between 5ºC and 10ºC (Sahin, 2016).

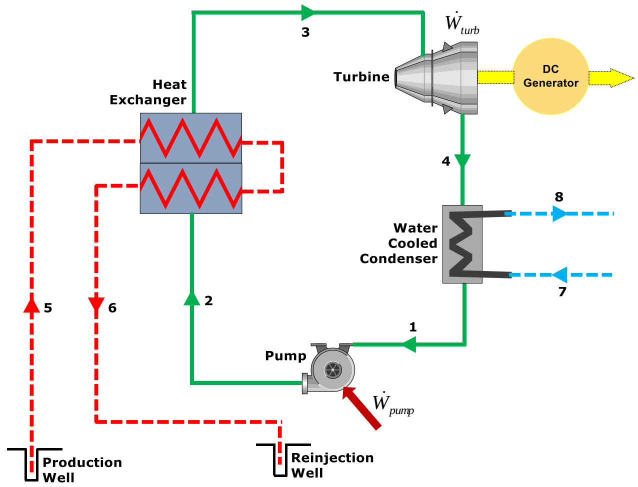


Figure 3. Schematic configuration of Afyon Geothermal Power Plant (AFJES).

The power input to the production and circulation pumps is usually small compared to turbine power. However, the power consumed by the cooling fans in the condenser can be up to 20 percent or more of the turbine power. Ambient temperature has a considerable effect on the power production of air-cooled binary geothermal power plants. As a result of reduced turbine power and increased fan power at higher ambient temperatures, the power output from such a plant decreases by up to 50 percent from winter to summer (Kanoglu and Bolatturk, 2008).

THERMODYNAMIC MODELING OF PLANT

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 vo-lume has been conserved mass, energy, entropy, and exergy. The equation equilibriums for the plant are as follows (Abusoglu and Kanoglu, 2008).

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

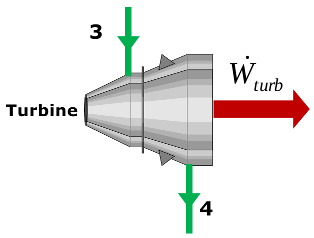
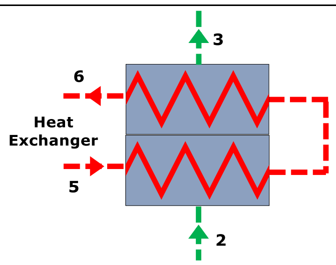
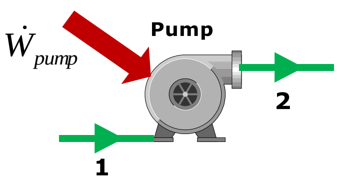
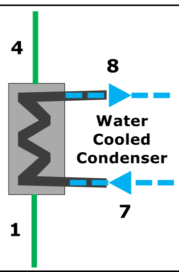
$$\dot{Q} + \dot{W} = \sum \dot{m}_e h_e - \sum \dot{m}_i h_i \quad (2)$$

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

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

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 ºC. Geothermal water mass flow rate, $\dot{m}_{geo}$ = 150 kg/s. Dead state temperature, T_0= 14 ºC. Optimum flash process pressure, P_5= 143.4 kPa. Binary turbine inlet pressure, P_3= 2800 kPa. Turbine isentropic efficiencies, η_{turb} = 90%. Analysis environment dead state pressure, P_0= 89.4 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.

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

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

The energy input to the binary geothermal power plant can be written from the Fig. 1 as:

$$\dot{E}_{geo} = \dot{m}_{geo}\left(h_5 - h_6\right) \quad (5)$$

The power outputs from the binary cycle can be written as:

$$\dot{W}_{turb} = \dot{m}_R\left(h_3 - h_4\right) \quad (6)$$

$$\dot{W}_{pump} = \dot{m}_R\left(h_2 - h_1\right) \quad (7)$$

$$\dot{W}_{net,binary} = \dot{W}_{turb} - \dot{W}_{pump} \quad (8)$$

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

$$\eta = \frac{\dot{W}_{net,geo}}{\dot{E}_{geo}} = \frac{\dot{W}_{net,binary} - \dot{W}_{parasitic}}{\dot{m}_{geo}\left(h_{geo} - h_0\right)} \quad (9)$$

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

$$\varepsilon = \frac{\dot{W}_{net,geo}}{\dot{E}x_{geo}} = \frac{\dot{W}_{net,binary} - \dot{W}_{parasitic}}{\dot{m}_{geo}\left(h_{geo} - h_0 - T_0\left(s_{geo} - s_0\right)\right)} \quad (10)$$

The binary working fluid is pumped to the binary heat exchanger for energy conversion with geothermal water to finish the thermodynamic cycle. Fig. 4 shows the binary working fluid of R134a operation on a temperature entropy diagram. This is an important decision parameter for R134a, because it is a proper thermodynamic fluid in the binary geothermal power plant. So there is no moisture in the binary turbine under these current conditions.

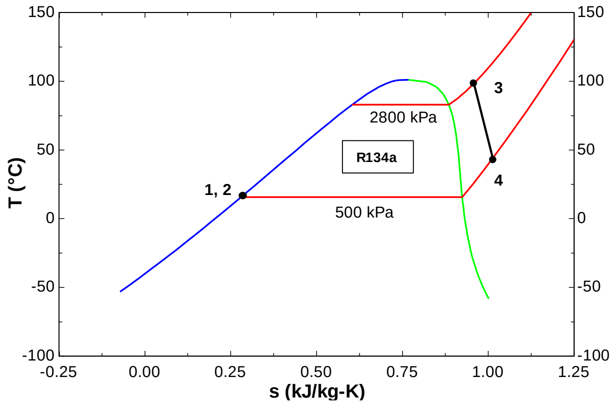


Figure 4. Temperature entropy (*T*-*s*) diagram of binary cycle.

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). The energy efficiency of the binary plant can be expressed on the geothermal water heat input to binary plant. The heat transfer process between the geothermal water and binary working fluid is shown in Fig. 5. The state points refer to Fig. 3. Binary working fluid should be vaporized completely (state h_{pp} to $h_{f,binary}$) and superheated by the geothermal water (state $h_{f,binary}$ to 3) as the water temperature is decreased from T_5 to T_{pp}. binary working fluid is heated from T_2 to T_{vap} as the temperature of geothermal water is decreased from T_{pp} to T_6. To achieve this heat transfer, there must be a temperature difference between the vaporization temperature of the binary working fluid (state h_{pp}) and temperature of geothermal water at state pp. this temperature differences is called pinch point temperature difference ΔT_{pp}. The state "pp" is called pinch point of geothermal water. An application of the energy conversion principle on this binary heat exchanger gives the fallowing equations (Kanoglu and Bolatturk, 2008):

$$\dot{m}_{geo}\left(h_5 - h_{pp}\right) = \dot{m}_{binary}\left(h_3 - h_{f,\ binary}\right) \quad (11)$$

$$\dot{m}_{geo}\left(h_{pp} - h_6\right) = \dot{m}_{binary}\left(h_{f,\ binary} - h_2\right) \quad (12)$$

Here $\dot{m}_{geo}$ and $\dot{m}_{binary}$ are the mass flow rates of geothermal water and binary working fluid, respectively, and h is the state enthalpy of fluid flow. Solving these equations simultaneously gives the mass flow rate of binary working fluid and exit the exit temperature of geothermal water when the initial temperature of geothermal water and binary working fluid, the exit temperature of binary working fluid and the pinch point temperature differences ΔT_{pp} are known. The value of ΔT_{pp} is usually taken between 5ºC and 10ºC, respectively (Kanoglu and Bolatturk, 2008). The vaporization temperature and the pinch point temperature of this plant are calculated to be 82.86°C and 87.86°C, respectively. Also, these design considerations and calculations give an exit temperature of geothermal water of 70°C at the binary heat exchanger outlet state.

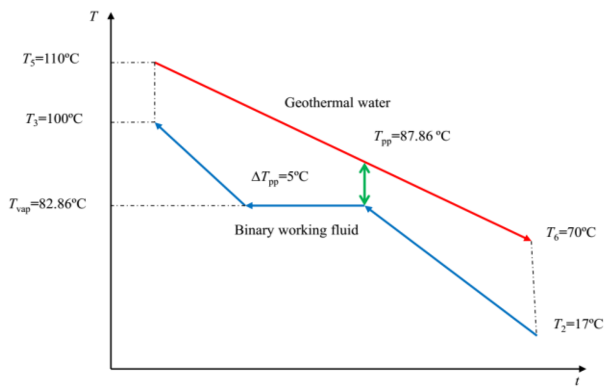


Figure 5. Plant heat transfer process in the binary heat exchanger.

Energy and exergy characteristics for each state of the system in Fig. 3 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, 2019).

Table2. Calculated thermodynamic properties of binary power plant.

State	Fluid	P (kPa)	T (ºC)	$\dot{m}$ (kg/s)	h(kJ/kg)	s(kJ/kgºC)	ex(kJ/kg)	$\dot{E}x$ (kW)
0	Geothermal water	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	6501	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 water	1650	110	150	461.4	1.419	58.9	8835
6	Geothermal water	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

The thermodynamic analysis is critical because it forms the basis of thermoeconomic 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

THERMOECONOMIC MODELING OF PLANT

Thermoeconomic 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 (Bejan et al., 1996):

$$\sum_{in} \dot{C}_{k,in} + \dot{Z}_k^T + \dot{C}_k^Q = \sum_{out} \dot{C}_{k,out} + \dot{C}_k^W \quad (13)$$

Here

$$\dot{C} = c \times \dot{E}x \quad (14)$$

For any k component, the exergy rates of inlet and exit are calculated by using exergy relations. $\dot{Z}^T$ 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 (Bejan et al., 1996):

$$\dot{Z}_k^T = \dot{Z}_k^{IC} + \dot{Z}_k^{OMC} \quad (15)$$

The economic analysis results of the power plant and equipments with Aspen Plus program in the computer environment are given in Table 3 (Aspen Plus, 2014).

Table 3. The cost rates associated with the components of the plant (Aspen Plus, 2015).

System 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			

THERMOECONOMIC COST RELATIONS OF PLANT

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

$$\dot{C}_i = c_i \dot{E}x_i = c_i(\dot{m}_i e_i) \quad (16)$$

$$\dot{C}_e = c_e \dot{E}x_e = c_e(\dot{m}_e e_e) \quad (17)$$

$$\dot{C}_w = c_w \dot{W} \quad (18)$$

$$\dot{C}_q = c_q \dot{E}x_q \quad (19)$$

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

$$\sum_e \left(c_e \dot{E}x_e\right)_k + c_{w,k}\dot{W}_k = c_{q,k}\dot{E}x_{q,k} + \sum_i \left(c_i \dot{E}x_i\right)_k + \dot{Z}_k^T + \sum_i \left(c_i Ex_i\right) \quad (20)$$

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. The cost rates associated with the fuel ($\dot{C}_F$) and product ($\dot{C}_P$) of a component are obtained simply by replacing the exergy rates ($\dot{E}x$) given in Table 2 by cost rates ($\dot{C}$). Table 4 defines the expressions of cost rates associated with fuel and product of the components contained in Table 2. The cost rate associated with fuel or product of a component contains the cost rates of the same streams used in the same order and with the same sign as in the definition of the exergy of fuel or product.

Table 4. Cost balance equations and auxiliary equations for the exergy costing of 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	$\dot{C}_3 + \dot{Z}_{BT} = \dot{C}_{W_{BT}} + \dot{C}_4$	$c_3 = c_4$ $c_{electricity}$ (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	$\dot{C}_1 + \dot{C}_{W_P} + \dot{Z}_{BP} = \dot{C}_2$	c_1 (known) c_2 (variable)

THERMOECONOMIC OPTIMIZATION OF PLANT

Thermal system optimization is the process to find the conditions that give maximum and minimum values of the plant efficiency and electricity cost. The plant manufacturer does not try to design the system to provide the minimum total cost to the consumer during the economic life of the equipment. Optimization of the plant is a complicated procedure generally involving many thermodynamic and economic variables. Reducing the difficulties of this process breaking up the procedure into many relatively simple optimization processes is usually helpful. One aspect of the overall problem which can be often treated separately before the main thermoeconomic optimization is optimization of the thermodynamic variables of the plant components with the thermodynamic and economic boundary conditions. In this study, thermoeconomic optimization was performed using the genetic algorithm method which is a subprogram of EES software. As given below Fig. 6 shows the base procedure of a genetic algorithm optimization (Leiva-Illanes et al., 2018).

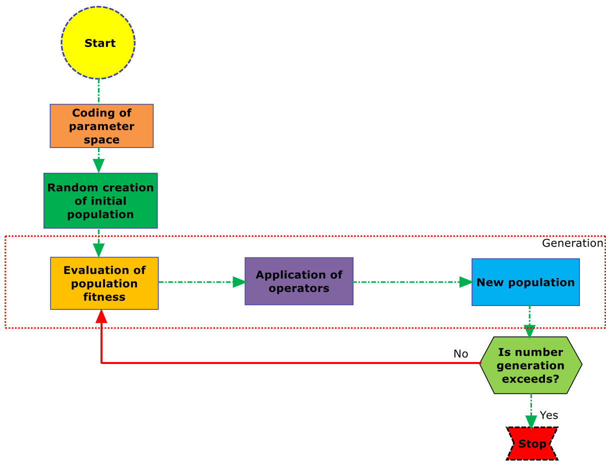


Figure 6. Optimization procedure of a genetic algorithm method (Leiva-Illanes et al., 2018).

The system has two objective functions for the optimization as shown in Fig. 7. These are the exergy efficiency and the cost of electricity generated by the plant. Optimization has been performed by analyzing how all components of the system response due to thermoeconomic analysis. For this purpose, economic cost analyzes were made with Aspen Plus program, and optimization calculations were coded with EES program. Because EES is a thermodynamically based analysis program, it provides a thermodynamic choice of design variables for thermal systems and convenience in monitoring the thermodynamic response of the system. Thermodynamic boundary conditions can be considered account by optimizing the EES program. In this study, optimization method with genetic algorithm was selected from the sub-library of EES software. The entire system is coded and optimized by design variables and thermodynamic boundary conditions. The genetic algorithm optimization is a search and optimization method that works in a similar way to the change process observed in the universe. According to the principle of finding the best in a complex multi-dimensional search space, it is the best solution for the system. The parameter $\dot{C}_{elec}$ must provide the energy corresponding to the primary parameter values in Fig. 7 so that the maximum energy output and minimum electricity cost values can be obtained from the plant.

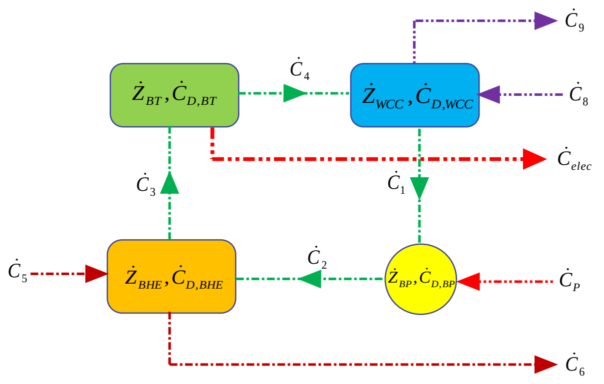


Figure 7. Thermoeconomic optimization flow diagram of the plant.

In the plant, the number of individuals in the population, the number of generations to explore, and the maximum mutation rate were considered as 1000, 0.317, and 16 in the EES program, respectively. Thermodynamically boundary conditions of the variables considered for this system are: 100≤ P_1≤1000 kPa, 5≤ΔT_{pp}≤30 °C, 1000 ≤ P_2≤ 3000 kPa, and 6≤ i ≤10 %, respectively. The decision variables are randomly generated for the above acceptable ranges.

RESULTS AND DISCUSSION

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 8 and 9. 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 water cooled condenser, representing 1227 kW and 1021.2 kW of the total exergy destruction in the cycle, respectively. The causes of exergy destruction in the plant included heat exchanger loss, turbine and pump losses, the exergy of the reinjected geothermal water, and the exergy of the R134a lost in the water-cooled condenser. This power plant is used Akarçay river water as cooling water in the condenser unit (Sahin, 2016). The average temperature will not change as the river water temperature constant throughout the year. Therefore, the water-cooled condensing unit will be more efficient for the plant.

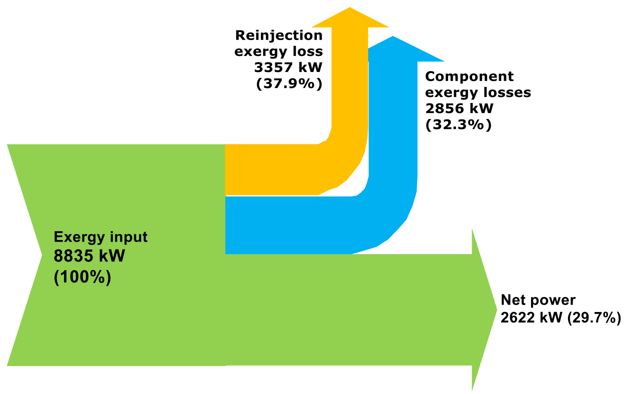


Figure 8. Exergy rate diagram of Afyon Geothermal Power Plant (AFJES).

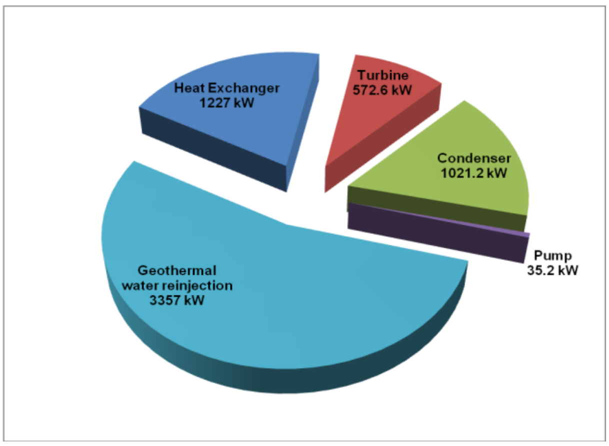


Figure 9. Exergy destructions in the components of the plant.

Thermoeconomic 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 thermoeconomic 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. Thermoeconomic results of the Afyon Geothermal Power Plant (AFJES).

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.10 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. In order to reduce the exergetic cost of electricity production, it is also considered to increase plant efficiency, to reduce exergy losses and to optimize operating conditions 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. Another important parameter of the classification of the working fluid performance is the unit work versus to specific geothermal water consumption that is mass flow rate of geothermal water to the net work output to the plant. The parameter is defined as β

$$\beta = \frac{\dot{m}_{geo}}{\dot{W}_{net}} \tag{21}$$

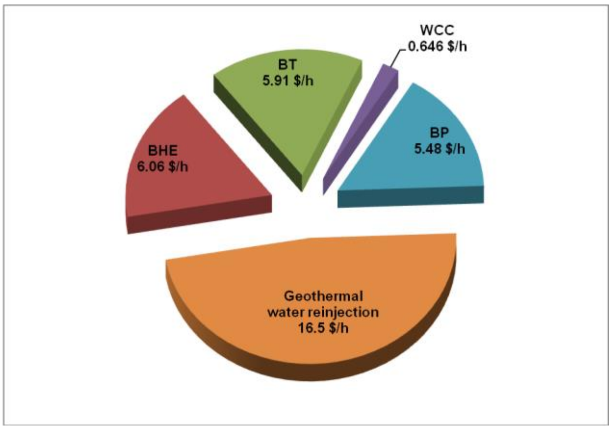


Figure 10. Distrubution of exergetic cost destruction rate diagram of the plant.

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 $T_{geo,in}$ = 110ºC and $T_{geo,out}$= 70ºC.
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%. The electricity cost production of the binary geothermal plant is the lowest when the working fluid R134a is used.

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

Fluids	β (kg/kJ)	$\dot{W}_{net}$ (kW)	η (%)	ε (%)	$C_{electrity}$ ($/kWh)
R134a	0.05721	2622	10.4	29.7	0.0233
Isobutane	0.06381	2351	9.3	26.6	0.0245
n-pentane	0.1282	1170	4.6	13.24	0.0674

Table 7 illustrates the use of the thermoeconomic 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 thermoeconomic methodology, recognize that the values of all thermoeconomic variables depend on the components (binary heat exchanger, turbine, pump,.

Table 7. Energetic and exergetic analyses results for the subsystems in 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)	r (%)	f (%)
Binary heat exchanger	5478	4251	1227	23.5	77.6	1.372	2.867	6.06	65.6	56.0
Binary turbine	4045	3473	572.6	10.9	85.8	2.867	6.470	5.91	70.3	59.1
Water cooled condenser	405.7	378	27.73	0.5	93.1	6.469	3.099	0.646	89.0	92.2
Binary pump	235.6	200.4	35.2	0.67	85.0	6.469	3.510	5.486	72.7	75.8
Geothermal water reinjection	8835	2622	3357	-	-	-	-	16.58	-	-
Overall System	10,164	8302	5219	35.7	81.6	1.372	6.470	13.44	297.6	283.1

water-cooled condenser). The accompanying Table 7 summarizes the thermoeconomic parameters calculated for each component of the binary geothermal power plant using data from Fig. 2., and definitions from Tables 4 and 5. The parameters include the exergy efficiency ε, exergy destruction rate, exergy destruction ratio y^*, average cost per unit of fuel exergy and product exergy, cost rate of exergy destruction, investment Z, the relative cost of difference r, and exergoeconomic factor f. The average exergy cost of geothermal water as a fuel input from the plant is calculated to be 1.372 $/GJ, and then, the corresponding exergy cost rate is calculated to be 43.6 $/h, respectively

Thermoeconomic optimization

In this study, the optimization process was applied to the plant by genetic algorithm, and the obtained results were examined. Proper operation conditions will be defined by optimization, and the plant will work more efficiently. Therefore, the plant will operate more efficiently, so that more power will be generated and the unit cost of the generated electricity will be reduced. For this reason optimization process is an essential tool for energy systems. The current power capacity of the Afyon Geothermal Power plant is 2622 kW, while this optimization capacity is 3461 kW. However, the cost of the electricity produced from the plant is 0.0233 $/kWh, while the optimization process result is 0.0176 $/kWh. Therefore, the unit cost of electricity from the plant is reduced by 24.3% with the optimization process. Due to this cost change, the plant's payback period has decreased from 3.36 to 2.87 years. This decrease also has a seriously positive effect on the annual profit and benefit-cost ratio. This value has a great proposition for energy project investments. Energy systems are directly related to investment and product costs. In this respect, optimization process will be very beneficial regarding thermodynamic performance and cost analysis of the plant.

Parametric study 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 per-formed 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. 8. The parametric study showing the power output was performed at temperatures between 100 and 150°C. Fig. 8 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 110ºC to 6633 kW at 150ºC, respectively.

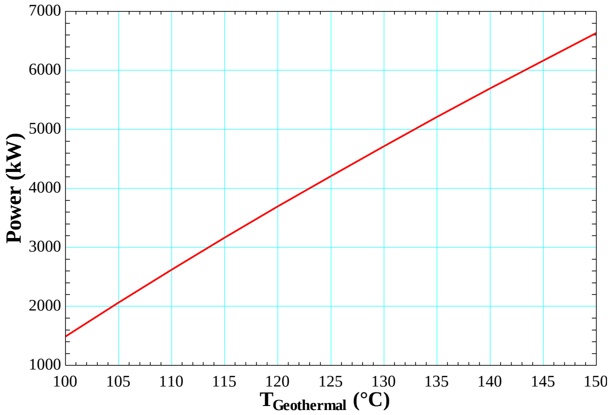


Figure 11. Power production of plant with geothermal water temperature

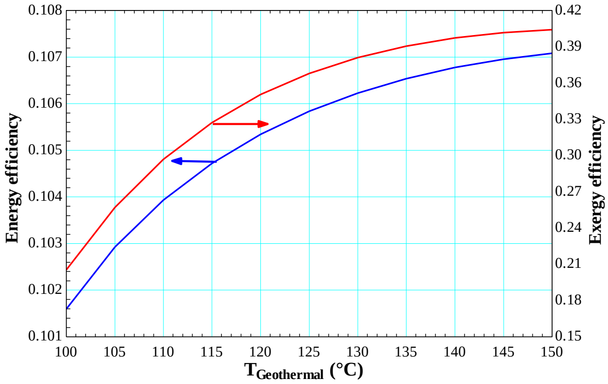


Figure 12. Thermodynamic performance evaluation of the plant.

Fig. 12 shows the variation of energy and exergy efficiencies with respect to the geothermal water temperature. The plant energy and exergy efficiencies simultaneously increase with the geothermal water temperature increases. The reason for the increase in efficiencies is that the unit mass flow rate of geothermal water has more intensive energy. The efficiencies will decrease at a point logarithmically, because plant working conditions must be optimized and reorganized according to the new geothermal water temperature of the plant.

The variation of electricity cost concerning the geothermal water temperature is shown in Fig. 13. 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.

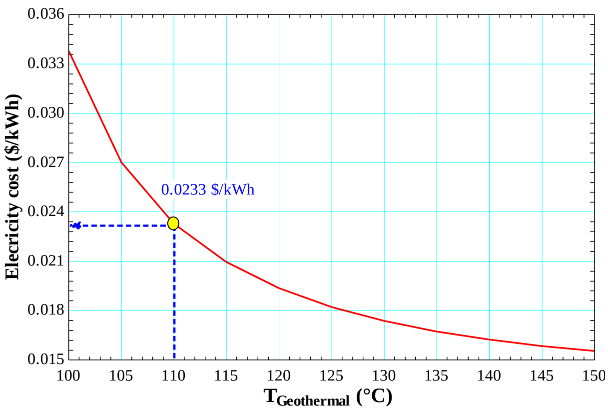


Figure 13. Electricity cost with geothermal water temperature.

The variation of plant power and des7truction cost rate for the different geothermal water temperatures of the different conditions are shown in Fig. 14. The electricity cost as linearly increased with the increase of the geothermal water temperature because more energy can be used and obtained from the same amount of geothermal water. However, the exergy destruction cost rate of the plant increases with geothermal water increases. The evaluation is suitable because the exergy destruction cost rate is rather than low to the production cost rate of the plant.

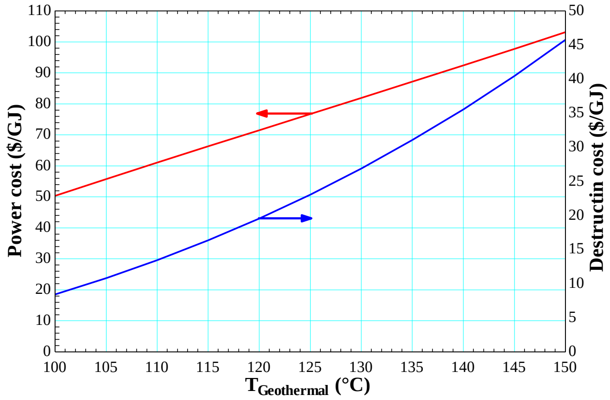


Figure 14. Variation of plant power and destruction cost rate with respect to the geothermal water temperature.

Fig. 15 shows the variation of plant power and destruction cost rate with respect to the geothermal water temperature. Geothermal water exergetic energy cost value as a fuel input to the plant increases with geothermal water temperature increases because energy quality of the water is higher than at low temperatures states. But reinjection geothermal water cost value inversely decreases with geothermal water temperature increase. And also, differences of the destruction values are very low and that can be neglected range of the destruction cost rate.

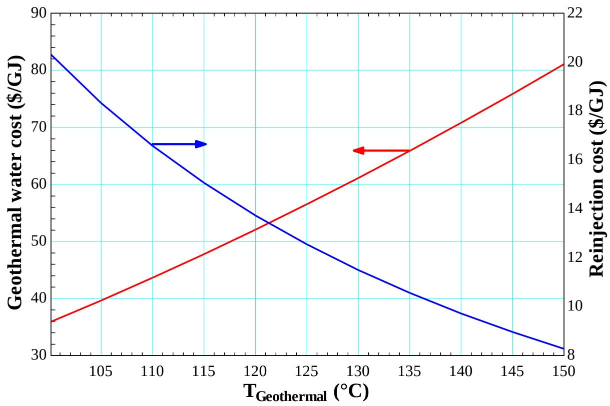


Figure 15. Variation of plant power and destruction cost rate with respect to the geothermal water temperature.

The annual total revenue for the plant is collected in given year through the market cost of electricity to supply the plant operating for all expenses incurred in the same year and to supply reliable economic plant operation. If the plant produces one product, its unit cost can be calculated directly from the total annual revenue cost. The annual revenue of the plant electricity production cost is calculated as (Dhillon, 2009):

Annual electricity production= (Net power output) × (Operating time)
= (2622 kW) × (8322) = 21,820,284 kWh/year

Total cost of investment = (3500 $/kW) × (2622 kW)
= 9,177,000 $

The plant payback period is defined as the length of time required for the cash inflows received from the plant to recover the original cash outlays required by the initial cost of investment. The purchase cost guaranteed of geothermal electricity is 0.132 $/kWh by the government (EPDK, 2017). Calculation of the plant simple payback period is relatively simple. The fallowing relations are expressed:

Simple payback period (SPP) = (Total cost of investment)/(Potential Annual Revenue - OMC)

Annual Potential Revenue = (Annual electricity production) × (Electricity market cost)
= (21,820,284 kWh/year) × (0.132 $/kWh)
= 2,880,277 $/yr
SPP=9,177,000 $/ (2,880,277 -150,000 $/yr)
= 3.36 years.

Fig. 16 shows the variation of plant power and destruction cost rate with respect to the geothermal water temperature. The pant payback period logarithmically decreases with geothermal water temperature linearly increases. When the market cost of the electricity is 0.132 $/kWh and geothermal water temperature is 110°C, according to the current working condition of the plant, the simple payback period of the plant is calculated to be 3.36 years.

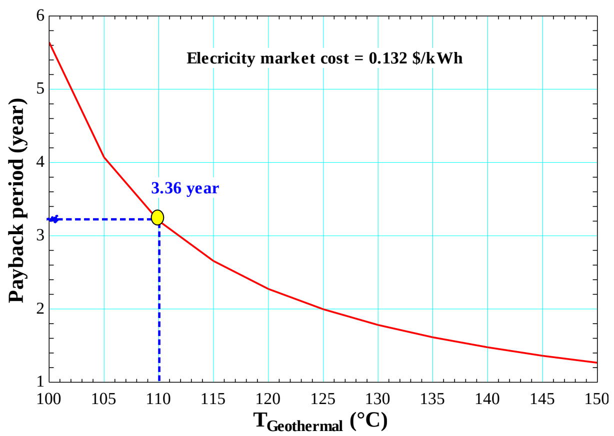


Figure 16. Plant payback period with respect to the geothermal water temperature.

CONCLUSIONS

Each geothermal power plant may have differences in design according to the application areas. The responses of the system based on exergoeconomic design values can be calculated in advance with this study. If the system does not provide the design values in the actual parameters, the reasons for loss of efficiency will be investigated, and studies can be made to improve the system efficiency. The high cost of the heat transmission line and the application difficulties are significant problems when geothermal resources are far from the settlements. In these cases, 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. 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:

Geothermal power plants are cyclic systems that receive heat from a geothermal source, convert some of it to work, and reject the rest to the ground. So, in this plant, the exergy input by this power plant is 8835 kW and the rate of heat rejection is to be determined as 3357 kW and this value correspond to 37.9 % of totally exergy input by the geothermal water. Energy and exergy values inputs from the geothermal water are evaluated with the base assumptions to be 62,079 kW and 8835 kW, respectively. According to the evaluated geothermal input energy values, the optimized net power generation from the plant is calculated to be 3461 kW. The energy and exergy efficiencies were evaluated as 10.4% and 29.7% for Afyon Geothermal Power Plant (AFJES). The energy production of a binary plant can be increased by good conservation measures such as operating parameters of plant longest time possible and for optimum longest duration, and it is important to clean the condenser coils.

The optimized exergetic cost of electricity produced of the plant are calculated to be 0.01763 $/kWh with the thermoeconomic method respectively. The plant exergy cost rate of product (net electricity) and exergy destruction cost rate by thermoeconomic analysis is calculated to be 61.7 $/h and 13.44 $/h, respectively. The exergy cost rate of geothermal water as a fuel and reinjection of the plant are determined as 43.64 $/h and 16.58 $/h, respectively. Internal and external destruction rate of cost allocation is determined as 30.0 $/h. The annual potential revenue of the plant is estimated to be 2,880,277 $/yr with simple payback period of 2.87 years. It has been observed that the current performance of the system can be improved significantly with the optimization process. This improvement is 24.2% in net power generation and 24.3% in electricity cost.

ACKNOWLEDGMENT

This study is sponsored by The Scientific and Technological Research Council of Turkey (TUBITAK) under the project 218M739. This support is greatly appreciated.

REFERENCES

Abusoglu, A. and Kanoglu, M., 2008, First and second law analysis of diesel engine powered cogeneration systems, *Energy Conversion and Management*, 49(8), 2026-2031.

Aksoy, N., 2014, Power generation from geothermal resources in Turkey, *Renewable Energy*, 68, 595-601.

Aspen Plus Software, 2015, Aspen Technology Incorporated., Ten Canal Park, Cambridge, MA, USA. www.aspentech.com.

Balcilar, M., Ozdemir, Z. A., Ozdemir, H. and Shahbaz, M., 2018, The renewable energy consumption and growth in the G-7 countries: Evidence from historical decomposition method, *Renewable Energy*, 126, 594-604.

Bejan, A., Tsatsaronis, G. and Moran, M.J., 1996, *Thermal Design And Optimization*. (First Ed.), John Wiley & Sons.

Cengel, Y. A. and Boles, M.A., 2015, *Thermodynamics: An Engineering Approach*, (Seventh Ed.) McGraw-Hill.

Coskun, A., Bolatturk, A. and Kanoglu, M., 2014, Thermodynamic and economic analysis and optimization of power cycles for a medium temperature geothermal resource, *Energy conversion and management*, 78, 39-49.

Dhillon, B.S., 2009, *Life cycle costing for engineer*, (First Ed.), Crc Press.

DiPippo, R., 2007, Ideal thermal efficiency for geothermal binary plants, *Geothermics*, *36*(3), 276-285.
Yari, M., 2010, Exergetic analysis of various types of geothermal power plants, *Renewable Energy*, 35(1), 112-121.

Ergun, A., Ozkaymak, M., Aksoy Koc, G., Ozkan, S. and Kaya, D., 2017, Exergoeconomic analysis of a geothermal organic Rankine cycle power plant using the SPECO method, *Environmental Progress & Sustainable Energy*, 36(3), 936-942.

F-Chart Software, EES, engineering equation solver. In: F-Chart Software (2019), Internet Website, www.fchart.com/ees/ees.shtml

Hanbury, O. and Vasquez, V.R., 2018, Life cycle analysis of geothermal energy for power and transportation: A stochastic approach, *Renewable Energy*, 115, 371-381.

Heberle, F., Hofer, M., Ürlings, N., Schröder, H., Anderlohr, T. and Brüggemann, D., 2017, Techno-economic analysis of a solar thermal retrofit for an air-cooled geothermal Organic Rankine Cycle power plant, *Renewable Energy*, 113, 494-502.

Internet, 2017, www.epdk.org.tr/tr/Dokumanlar/elektrik/yekdem/2017.

Kahraman, M., Olcay, A.B. and Sorgüven, E., 2019, Thermodynamic and thermoeconomic analysis of a 21 MW binary type air-cooled geothermal power plant and determination of the effect of ambient temperature variation on the plant performance, *Energy Conversion and Management*, 192, 308-320.

Kanoglu, M., 2002, Exergy analysis of a dual-level binary geothermal power plant, *Geothermics*, 31(6), 709-724.

Kanoglu, M. and Bolatturk, A., 2008, Performance and parametric investigation of a binary geothermal power plant by exergy, *Renewable Energy*, 33(11), 2366-2374.

Kanoglu, M. and Dincer, I., 2009, Performance assessment of cogeneration plants, *Energy conversion and management*, 50(1), 76-81.

Karadas, M., Celik, H. M., Serpen, U. and Toksoy, M., 2015, Multiple regression analysis of performance parameters of a binary cycle geothermal power plant, *Geothermics*, 54, 68-75.

Karimi, S. and Mansouri, S., 2018, A comparative profitability study of geothermal electricity production in developed and developing countries: Exergoeconomic analysis and optimization of different ORC configurations, *Renewable Energy*, 115, 600-619.

Kasaei, M. J., Gandomkar, M. and Nikoukar, J., 2017. Optimal management of renewable energy sources by virtual power plant, *Renewable Energy*, 114, 1180-1188.

Korkmaz, E. D., Serpen, U. and Satman, A., 2014, Geothermal boom in Turkey: Growth in identified capacities and potentials, *Renewable Energy*, 68, 314-325.

Kolahi, M. R., Nemati, A. and Yari, M., 2018, Performance optimization and improvement of a flash-binary geothermal power plant using zeotropic mixtures with PSO algorithm, *Geothermics*, *74*, 45-56.

Koroneos, C., Polyzakis, A., Xydis, G., Stylos, N. and Nanaki, E., 2017, Exergy analysis for a proposed binary geothermal power plant in Nisyros Island, Greece, *Geothermics*, *70*, 38-46.

Leiva-Illanes, R., Escobar, R., Cardemil, J. M. and Alarcón-Padilla, D. C., 2018, Comparison of the levelized cost and thermoeconomic methodologies–Cost allocation in a solar polygeneration plant to produce power, desalted water, cooling and process heat, *Energy Conversion and Management*, 168, 215-229.

Sahin, C., 2016, *Electricity Generation With Organic Rankine Cycle (ORC) In Low Temperature Geothermal Field And Modeling Of Afyon Geothermal Electric Production Co*., M.S. Thesis, Electrical and Electronics Engineering, Kütahya Dumlupınar University, Turkey.

Shokati, N., Ranjbar, F. and Yari, M., 2015, Exergoeconomic analysis and optimization of basic, dual-pressure and dual-fluid ORCs and Kalina geothermal power plants: A comparative study, *Renewable Energy*, 83, 527-542.

Wang, J., Wang, J., Dai, Y. and Zhao, P., 2015, Thermodynamic analysis and optimization of a flash-binary geothermal power generation system, *Geothermics*, 55, 69-77.

Yilmaz, C., 2017, Thermodynamic and economic investigation of geothermal powered absorption cooling system for buildings, *Geothermics*, 70, 239-248.

Zheng, B., Xu, J., Ni, T. and Li, M., 2015, Geothermal energy utilization trends from a technological paradigm perspective, *Renewable Energy*, 77, 430-441.