

# Thermoeconomic Cost Analysis of Solar and Geothermal Energy Powered Cooling and Power Cogeneration

\*<sup>1</sup>Ozan Sen and <sup>1</sup>Ceyhun Yilmaz

\*<sup>1</sup> Department of Mechanical Engineering, Afyon Kocatepe University, Technology Faculty,  
03200 Afyonkarahisar, Turkey

## Abstract

In this study, geothermal and solar energy assisted cogeneration energy system has been modeled to supply residences' electricity and cooling requirements. The geothermal water from the geothermal resource and the heat transfer fluid heated in the parabolic collector is used as the heat source in the absorption cooling system. Electricity is generated in the binary power plant with geothermal water and heat transfer fluid from the absorption cooling system. The generated electricity is supplied to the grid. Thermoeconomic analysis of the system is performed by using the Engineering Equation Solver (EES) program by using geothermal and solar energy values of Afyonkarahisar. The system's parametric study is performed by considering the different geothermal resource temperatures and solar radiation values. According to these results, the unit electricity and unit cooling costs produced in the system will be investigated. The optimum working conditions are investigated in producing and using the energy form (electricity-cooling) requirements.

**Keywords:** Geothermal energy, solar energy, thermoeconomic analysis, cogeneration.

## 1. Introduction

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. 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 [1].

Renewable energies are currently the fastest growing energy source in the world. Depletion and emission concerns over fossil fuel use and increasing government incentives can cause even higher growth in the use of renewable sources in the coming decades. An energy source is called renewable if it can be renewed and sustained without any depletion and any significant effect on the environment. It is also called alternative, sustainable, or a green energy source. Fossil fuels such as coal, oil, and natural gas, on the other hand, are not renewable, and they are depleted by use. They also emit harmful pollutants and greenhouse gases. Main renewable energy sources include solar, wind, hydro, biomass, and geothermal. Energies from ocean including wave and tidal energies are also renewable sources but they are currently not economical and the technologies are still in the experimental and developmental stage [2].

The total installed geothermal energy power in the world reached the level of 15,406 MW by the end of 2019, with an increase of 759 MW compared to the end of 2018. Top five countries in power generation capacity from geothermal energy; US, Indonesia, the Philippines, Turkey and New Zealand. Turkey ranks fourth in the world with 1526 MW capacity. The installed power of our country in geothermal energy investments is expected to reach 1700 MW by the end of 2020. Turkey aims to enter the top three in a short time with a stable investment [3]. In 2019, total PV installed power capacity increased by 115 GW worldwide in 2019 compared to the previous year. The PV market broke the 100 GW thresholds for the third time in a row and the market volume grew by 12%. Turkey, with 6 GW installed power capacity in the world rankings ranks 13th [4]. The best-known renewable source is solar energy. Although solar energy is sufficient to meet the entire energy needs of the world, currently it is not used as extensively as fossil fuels because of the low concentration of solar energy on earth and the relatively high capital cost of harnessing it. Another most popular renewable energy source is geothermal energy. Geothermal energy refers to heat of earth. High temperature underground geothermal fluid found in some locations is extracted and the energy of geothermal fluid is converted to electricity or heat. Geothermal energy conversion is one of the most mature renewable energy technologies. Geothermal energy is mostly used for electricity generation and district heating. Especially Afyonkarahisar province has a great potential in terms of geothermal and solar energy sources. In this study, the potential of the efficient use and alternative methods will be investigated [5].

In this study, geothermal and solar energy assisted cogeneration energy system has been modeled to supply residences' electricity and cooling requirements. The geothermal water from the geothermal resource and the heat transfer fluid heated in the parabolic collector is used as the heat source in the absorption cooling system. Electricity is generated in the binary power plant with geothermal water and heat transfer fluid from the absorption cooling system. The generated electricity is supplied to the grid. Thermoeconomic analysis of the system is performed by using the Engineering Equation Solver (EES) program by using geothermal and solar energy values of Afyonkarahisar. The system's parametric study is performed by considering the different geothermal resource temperatures and solar radiation values. According to these results, the unit electricity and unit cooling costs produced in the system will be investigated.

## 2. Materials and Method

### 2.1. Description of System

In this study, geothermal and solar energy assisted cogeneration energy system has been modeled to supply residences' electricity and cooling requirements. The geothermal water from the geothermal resource and the heat transfer fluid heated in the parabolic collector is used as the heat source in the absorption cooling system. Electricity is generated in the binary power plant with geothermal water and heat transfer fluid from the absorption cooling system. The generated electricity is supplied to the grid.

The overview of the cooling and power cogeneration system is given in Fig. 1. The cooling and power cogeneration system consists of two systems: the part where power is generated in the organic rankine cycle and the space cooling is made using the geothermal and solar energy-assisted absorption cooling cycle.

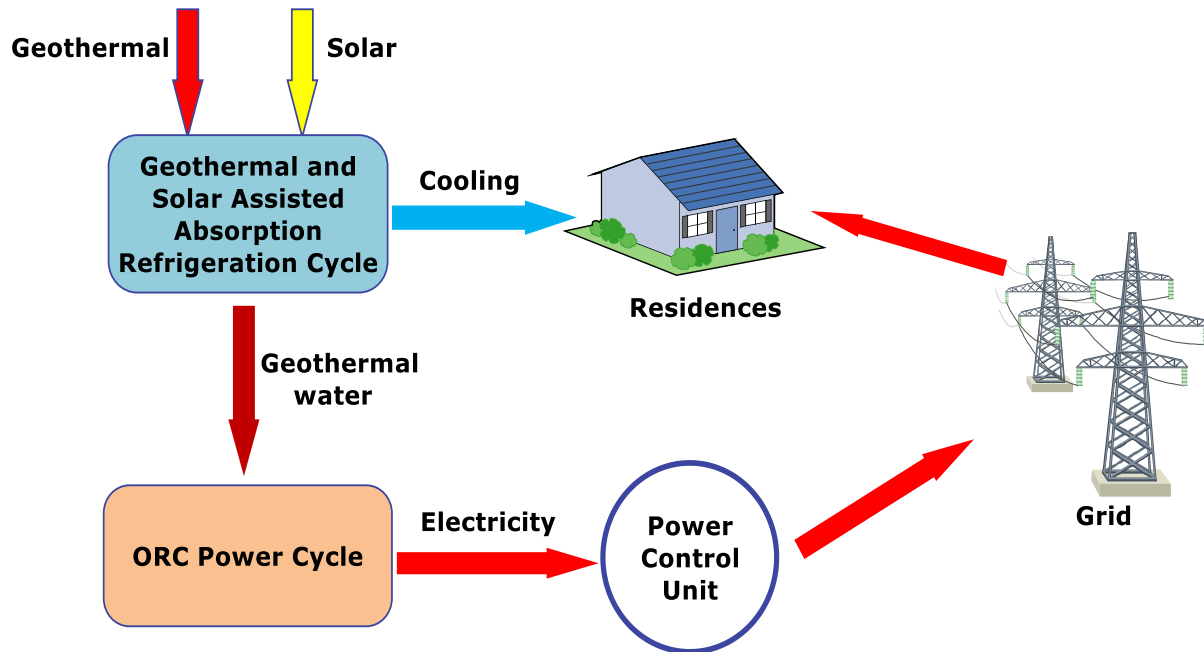


Figure 1. Solar and geothermal energy powered cooling and power cogeneration

### 2.2. Thermodynamic Modeling of Cooling and Power Cogeneration System

In accordance with the geothermal temperature of the region, organic rankine cycle was selected for the plant. Because the geothermal field of the region has the low temperature scale fields. In the organic rankine cycle, R134a fluid circulates as the working fluid. For solar energy, which is the other main source of the system; parabolic trough collector was selected due to its advantages such as high operating temperature and power output, storage capacity, compatibility with hybrid systems. Therminol VP-1 is used as heat transfer fluid in parabolic trough collectors. The average

monthly average solar irradiation of the region varies from 500-600 W/m<sup>2</sup>.

The electricity consumption and energy costs of cooling systems are at very high levels. Absorption cooling systems are economically interesting when a cheap thermal energy source with a temperature between 80 °C and 170 °C is available. Therefore, it would be appropriate to use geothermal and solar energy as a heat source in the absorption cooling system. Cooling systems with LiBr-H<sub>2</sub>O are the most suitable absorption systems for cooling applications. LiBr salt is used as an absorbent in the LiBr-H<sub>2</sub>O couple. LiBr salt has the advantage due to its stability in aqueous solution and low pressure in the absorber. LiBr-H<sub>2</sub>O double cooling systems operate at lower thermal energies than NH<sub>3</sub>-H<sub>2</sub>O double cooling systems and their performance coefficients (COP) are higher than NH<sub>3</sub>-H<sub>2</sub>O double cooling systems. In the light of this information, LiBr-H<sub>2</sub>O couple was used in the absorption cooling system in the cogeneration system. Thermodynamic analysis of the cogeneration system has been made assuming that the equipment operates under control volume and constant regime conditions. Pressure losses in the system are neglected. The isentropic efficiency of turbines and pumps has been accepted as 85% by using the current data of the manufacturers.

The actual coefficient of performance (COP) value of the absorption cooling system can be calculated by dividing the evaporator cooling capacity by the sum of the heat entering the generator and the pump work [6]:

$$COP_{ARC} = \frac{\dot{Q}_{cooling}}{(\dot{Q}_{gen} + \dot{W}_{pump})} \quad (1)$$

The exergy efficiency of the absorption cooling system can be calculated with the help of the following equation:

$$\varepsilon_{ARC} = \frac{-\dot{Q}_{cooling}(T_0/T_E - 1)}{\dot{Q}_{gen}(T_0/T_G - 1)} \quad (2)$$

Where TE is the evaporator temperature and TG is the generator temperature.

The energy efficiency for the overall system can be calculated by dividing the net electrical energy generated in the ORC cycle and the total cooling capacity of the absorption cooling system to the total heat energy entering the cogenerated energy system:

$$\eta_{overall} = \frac{\dot{W}_{net,elec} + \dot{Q}_{cooling}}{\dot{Q}_{geo,in} + \dot{Q}_{solar,in}} \quad (3)$$

For the overall system, exergy efficiency expression with the input-output exergy approach can be written as follows:

$$\varepsilon_{overall} = \frac{\dot{W}_{net,elec} + \dot{Q}_{cooling}((T_0/T_E) - 1)}{\dot{E}x_{geo,in} + \dot{E}x_{solar,in}} \quad (4)$$

### 2.3. Thermoeconomic Cost Analysis of Cooling and Power Cogeneration System

Thermoeconomics is a discipline that combines exergy analysis and economic principles. Thus, it is a very useful method to obtain a rational cost structure that cannot be achieved with traditional energy and economic analysis. When calculating costs in a system, the initial consideration should be given to a) defining the true costs of products and services, b) providing a reasonable source for pricing goods and services, c) providing a financing for control and similar expenses, d) providing information on which business decisions can be evaluated and based on. In conventional economic analysis, when writing the price balance, generally the whole system costs can be formulated as expressed in the following relation [7].

$$\dot{C}_{P,TOT} = \dot{C}_{F,TOT} + \dot{Z}_{TOT}^{CI} + \dot{Z}_{TOT}^{OM} \quad (5)$$

The cost value associated with the product of the system is equal to the total costs incurred during the production of the product. These costs consist of fuel cost, initial investment cost, and operating and maintenance costs. In the case of a single stream associated with a fuel and product, the fuel and product flow is used and is obtained by dividing the annual operating and maintenance costs and the annual contribution of capital investments by the value of the unit of time the system has been operating in a year, respectively. It is represented by the sum of these two variables and expressed as follows:

$$\dot{Z} = \dot{Z}^{CI} + \dot{Z}^{OM} \quad (6)$$

The capital recovery factor (CRF) can be calculated as follows depending on the interest rate (i) and the economic life of the equipment (n) [8]:

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1} \quad (7)$$

Thermoeconomic analysis was carried out by considering geothermal and solar energy assisted absorption cooling cycle and power plant together. First of all, the cooling cycle and power plant were coded and operated in the Aspen Plus program, and the purchase costs of the equipment were obtained. Then, in the EES program, the necessary data calculated for the system were coded into the program by us and the results of thermoeconomic analysis were obtained.

As it is known, it is very difficult to reach current economic data today. Although these economic data can be calculated with some approaches, this process takes a long time and the accuracy of the results is not certain. Due to all these baskets, taking advantage of the Aspen Plus program in our thermoeconomic analysis provides us a great advantage and convenience. With this program,

it is possible to perform energy analysis and to reach all economic data of thermal systems in the past and present and initial investment costs of system components.

### 3. Results

Energy, exergy and economic characteristics for each state of the system in Fig. 1 are calculated in this section. 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). The thermodynamic analysis is critical because it forms the basis of next thermoeconomic analysis. For this reason, the thermodynamic analysis must be done correctly.

As a result of the thermodynamic analysis, from the geothermal fluid and heat transfer fluid (Therminol VP-1), 25,261 kW of heat and 5578 kW of exergy were input to the cogenerated energy system. The geothermal fluid entered the absorption cooling system as a heat source with a temperature of 130 °C and a mass flow of 85 kg/s and a heat transfer fluid coming from the parabolic chute collector with a temperature of 145 °C and a mass flow of 0.2 kg/s. Considering these thermodynamic properties, the heat transferred to the heater ( $\dot{Q}_{gen}$ ) was calculated as 3634 kW. The cooling capacity of the evaporator was calculated as 2720 kW. The actual performance coefficient (COP) value of the absorption cooling system was calculated as 0.748 from Eq.1. The exergy efficiency of the absorption cooling system was calculated as 22.5% from Eq.2

With the geothermal fluid and heat transfer fluid coming from the absorption cooling system, 21,579 kW of heat and 4505 kW of exergy were input to the organic rankine cycle in which the electrical energy is generated. The net work obtained from the organic rankine cycle was calculated as 2235 kW. The energy efficiency of organic rankine cycle was calculated as 10.3% and exergy efficiency as 49.6%. The overall energy and exergy efficiencies of the system are calculated as 19.6 and 43.7 percent by using the Eq. 3 and 4.

The annual working hour for the system is 7446 hours and its economic life is 20 years. The annual interest rate (i, interest rate) we use in economic analysis has been accepted as 10%. Within the scope of the economic acceptances, the capital recovery factor (CRF) value was calculated as 0.1175. In Table 1 below created for the system, the purchased equipment costs (PEC) of the model equipment and the initial investment cost ratio ( $Z^{CI}$ ) are calculated. In this context, the total purchased equipment cost (PEC) of the equipment used in the model was calculated as \$ 1,554,100.

Table 1. System's purchasing costs and initial investment cost rates (Aspen Plus V11, 2019).

System components	PEC (\$)	$Z^{CI}$ (\$/h)
ORC-Pump	70,000	1.17
ORC-Heat exchanger	325,000	5.43

ORC-Turbine	480,000	8.028
ORC-Condenser	325,000	5.436
Pump-1	5000	0.083
Expansion valve-1	5000	0.083
Heat exchanger-1	22,000	0.367
Generator	100,000	1.672
Condenser	26,900	0.449
Expansion valve-2	5000	0.083
Evaporator	11,500	0.192
Absorber	94,200	1.575
Heat exchanger-2	11,500	0.192
Parabolic collector	72,000	1.203
Pump-2	1000	0.016
<b>Total Purchased Cost (PEC)</b>	<b>1,554,100</b>	-

Based on the SPECO method, sufficient number of auxiliary equations have been developed for system components with the help of F and P principles for the models developed and these equations and the cost balance equation based on exergy are given in Table 2 for the cogeneration system. By making technical acceptances, auxiliary equations were written and decoded in the computer environment in the EES program accordingly.

Table 2. Cost equations of system sub-components depending on exergy and auxiliary equations.

System components	Cost balance equations based on exergy	Auxiliary equations
ORC-Pump	$\dot{C}_1 + \dot{Z}_P + \dot{C}_{W_P} = \dot{C}_2$	$c_1$ (is known) $c_2$ (variable)
ORC- Heat exchanger	$\dot{C}_2 + \dot{C}_8 + \dot{C}_{11} + \dot{Z}_{HE} = \dot{C}_3 + \dot{C}_9 + \dot{C}_{27}$	$c_8 = c_9$
ORC-Turbine	$\dot{C}_3 + \dot{Z}_T = \dot{C}_{W_T} + \dot{C}_4$	$c_3 = c_4$ $c_{electricity}$ (variable)

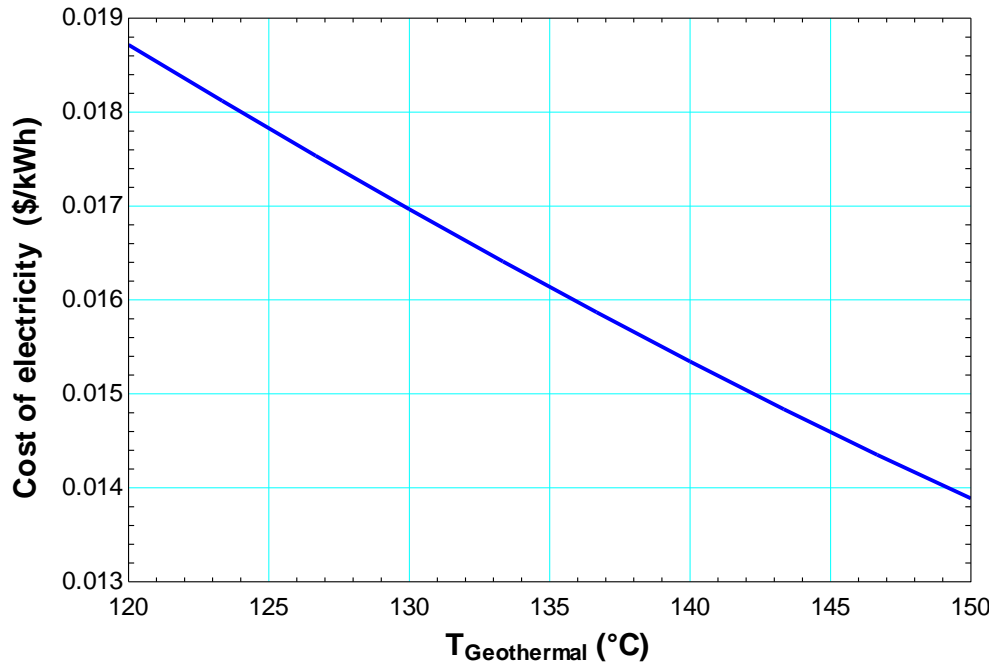
ORC-Condenser	$\dot{C}_4 + \dot{C}_5 + \dot{Z}_{WCC} = \dot{C}_1 + \dot{C}_6$	$c_5 = 0$
Pump-1	$\dot{C}_{12} + \dot{Z}_P + \dot{C}_{WP} = \dot{C}_{13}$	$c_{12}$ (is known)
Heat exchanger -1	$\dot{C}_{13} + \dot{C}_{15} + \dot{Z}_{HE} = \dot{C}_{14} + \dot{C}_{16}$	$c_{15} = c_{16}$
Generator	$\dot{C}_7 + \dot{C}_{10} + \dot{C}_{14} + \dot{Z}_{GEN} = \dot{C}_8 + \dot{C}_{11} + \dot{C}_{15} + \dot{C}_{18}$	$c_7 = c_8$
Condenser	$\dot{C}_a + \dot{C}_{18} + \dot{Z}_{CON} = \dot{C}_b + \dot{C}_{19}$	$c_a = 0$
Evaporator	$\dot{C}_{20} + \dot{C}_{22} + \dot{Z}_{EVA} = \dot{C}_{21} + \dot{C}_{23}$	$c_{22} = 0$ $c_{20} = c_{21}$
Absorber	$\dot{C}_c + \dot{C}_{17} + \dot{C}_{21} + \dot{Z}_{ABS} = \dot{C}_d + \dot{C}_{12}$	$c_c = 0$
Heat exchanger -2	$\dot{C}_{23} + \dot{C}_{25} + \dot{Z}_{DHE} = \dot{C}_{24} + \dot{C}_{26}$	$c_{25} = 0$ $c_{23} = c_{24}$
Parabolic collector	$\dot{C}_{28} + \dot{Z}_{PTC} = \dot{C}_{10}$	$c_{28}$ (is known)

The unit cooling cost was calculated as 0.074 \$/kWh (20.77 \$/GJ) in the absorption cooling cycle operated with a geothermal fluid with a temperature of 130 °C and a mass flow of 85 kg/s and a heat transfer fluid with a temperature of 145 °C and a mass flow of 0.2 kg/s. The unit cost (LCOE) of the electricity produced in the power plant operated with a geothermal fluid with a temperature of 120 °C and a mass flow of 85 kg/s and a heat transfer fluid with a temperature of 135 °C and a mass flow of 0.2 kg/s was calculated as 0.016 \$/kWh (4.71 \$/GJ).

#### 4. Discussion

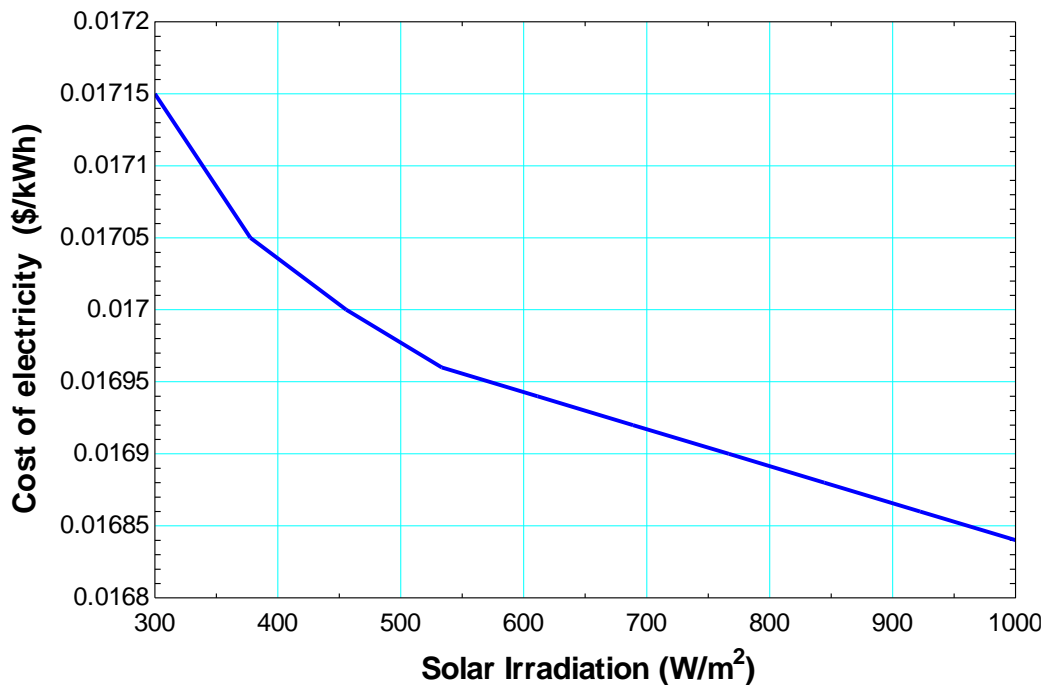
Parametric investigations of the plant are given below with some figures. Figure 2 shows the change in unit cost of electricity generated depending on the temperature of the geothermal fluid. The unit cost of electricity generated decreases linearly with the increase of the geothermal fluid temperature.





**Figure 2.** The change in the unit cost of electricity generated depending on the temperature of the geothermal fluid

Figure 3 shows the change in unit cost of electricity generated depending on solar radiation intensity. It has been observed that the unit cost of electricity produced decreases with the increase in solar radiation intensity.



**Figure 3.** The change in the unit cost of electricity generated depending on the intensity of solar radiation

## Conclusions

This study helps give a good insight to researchers and designers working in areas of hybrid renewable energies and cooling/electricity production systems for better operation and assessment. A solar and geothermal energy driven cooling/electricity cogeneration system is considered. Thermodynamic and thermoeconomics investigation of solar and geothermal powered system for power generation has allowed several main considerations to be drawn. In this paper, it has been analyzed the full time power load of the thermodynamic and thermoeconomics analysis of solar/geothermal sources and determined the performance of the cooling and electricity production system to be satisfactory. It has been shown that this solar and geothermal source can be utilized better for a case study of Turkey.

## Acknowledgements

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

## References

- [1] Yilmaz, C. Thermodynamic and economic investigation of geothermal powered absorption cooling system for buildings. *Geothermics*2017;70:239-248.
- [2] Shahin, M. S., Orhan, M. F., Uygul, F. Thermodynamic analysis of parabolic trough and heliostat field solar collectors integrated with a Rankine cycle for cogeneration of electricity and heat. *Solar Energy*2016;136:183-196.
- [3] <https://www.thinkgeoenergy.com/-2020>
- [4] <https://iea-pvps.org/snapshot-reports/snapshot-2020/>
- [5] Li, Y., Yang, Y. Thermodynamic analysis of a novel integrated solar combined cycle. *Applied energy*2014;122:133-142.
- [6] Cengel, Y. A., Boles, M. A. *Thermodynamics: An Engineering Approach*. 8th ed. McGraw-Hill; 2015.
- [7] Bejan A., Tsatsaronis G., Moran M. *Thermal Design and Optimization*. 1st ed. New York: Wiley; 1996.
- [8] Dhillon, B. S. *Life cycle costing for engineers*, Crc Press. 2009.