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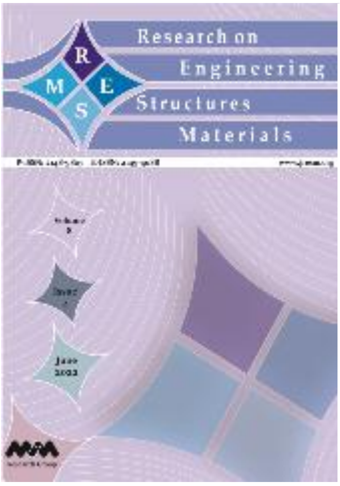

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Research Article

Energy and exergy analysis of a solar energy-based power generation system

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Abstract

Nowadays, energy is obtained from both fossil fuels and renewable energy sources. The use of fossil fuels causes climate change and global warming. The use of renewable energy systems ensures the reduction of greenhouse gas emissions and, as a result, the reduction of global warming. In this study, a solar-based electricity generation facility, which is one of the renewable energy sources, is discussed. The power generation potential of the solar system with integrated Rankine cycle under the changing climatic conditions of Iskenderun, which is a region with high solar energy potential, is investigated by thermodynamic analysis. A solar power tower was selected as the solar energy system in the facility. In the facility, electrical energy is obtained by sending the heat energy obtained from the solar power tower to the steam Rankine cycle. Energy and exergy analysis were performed to find the performance of the facility and the main sources of exergy destruction. As a result of the thermodynamic analysis, the net power obtained from the system increased with the increase of the input heat. During the day, 495.3 MWh/day of heat entered the system and 202.3 MWh/day of net power was obtained from this heat. The highest exergy destruction in the system occurred at 12:00. The highest exergy destruction occurred in the receiver at this hour and was calculated as 13.83 MW. The daily average energy and exergy efficiencies of the system were found to be 40.8% and 66.08%, respectively.

1. Introduction

The energy and environmental overlook of the world have become much worse day by day. Besides, the increase in technological developments along with the population significantly is increased the energy demand. To meet this demand, it is clearly seen in global data that coal, natural gas and oil are the most used fuels [1]. However, in addition to the limited use of fossil fuels, the negative effects of the pandemic period and political conflicts between countries as well as the limited fossil fuels is obstructed access to fossil fuels. This situation has revealed the necessity of using renewable energy sources more [2]. At the same time, fossil fuel usage has caused global climate change and increased health risks. Using renewable energy sources instead of fossil fuels is making it a necessity [3]. Solar energy has a huge energy source [4]. Solar energy is one of the most important renewable energy sources, an alternative to fossil fuels. Solar energy is an environmentally friendly, safe, practical, renewable energy source [5-6]. The use of renewable energy concerns sectors of activity such as industry, buildings, transportation and agriculture [7]. Recently, the efficiency of solar energy technologies has increased significantly and is more easily accessible. Despite the high installation costs of solar energy technologies, low operating cost makes them attractive. In addition, while fluctuations in the prices of fossil

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fuels are observed, solar energy is relatively stable for long periods [8]. For this reason, today, solar energy-based technologies are developed to meet the increasing energy demand [9]. Exergy analysis is an important method in the thermodynamic analysis of power systems. Exergy analysis is widely used, especially in revealing the quality of a system design and examining the improvement potential of the equipment used. When compared with the first law analysis, losses in the system could be determined both quantitatively and qualitatively with the exergy analysis [5].

Ahmadi and Toghraie[10] studied the steam cycle of a power plant in Iran. The system performance was examined by carrying out energy and exergy analysis of the cycle and its equipment. As a result of the analysis, it was found that the highest exergy destruction is performed in Boiler. Altarawneh et al. [11] performed the energy and exergy analysis of the hybrid fuel thermal power plant in Jordan. As a result of the analysis, it was found that the boiler caused the highest exergy destruction in the plant. In order to improve the performance of the plant, it has been suggested to increase the performance of the boiler. Although solar energy systems are used in many areas, the remarkable results obtained from solar tower power plants bring this field into the forefront. The steam Rankine cycle is the most widely used in concentrated solar energy from solar-based technologies. In low and medium-temperature applications, the organic Rankine cycle (ORC) is a promising alternative to the steam Rankine cycle. While water is used in the Steam Rankine cycle, organic fluid is used in the ORC. The choice of working fluid for ORC depends on the temperature of the heat source, ranging from 70°C to 400°C [12]. However, since turbine inlet temperature is high in the present study, the steam Rankine cycle is preferred. Some studies are focusing on solar tower power plants. Xu et al. [5] evaluated the performance of the solar tower power plant by performing energy and exergy analysis. They found that the central receiver and power cycle have the highest energy and exergy efficiency, respectively. Yagli et al. [13] performed parametric optimization of a solar power tower plant for the Iskenderun region. They found that the highest net power generation was at 1000°C at tower outlet temperatures varying between 500°C and 1000°C. The energy and exergy efficiencies of the plant were calculated as 45.81% and 47.19%, respectively. Zolfagharnasab et al. [14] investigated a solar tower with the Rankine cycle from a thermodynamic point of view. It was determined that the exergy efficiency of the receiver decreased from 57% to 52% with the increase in ambient temperature. It has been found that the increase in wind speed decreases energy and exergy efficiency. In addition, they found the optimum values of molten salt outlet temperature and velocity as 650 K and 2 m/s, respectively. Salilih et al. [15] analyzed a small-scale industrial waste heat-assisted solar tower power plant in their study. They claimed that using nanofluids instead of water as the cooling fluid in the condenser increases the solar system's efficiency. Different power cycles utilizing solar energy have also been used. Siddiqui and Almitani [16] performed the energy and exergy analysis of a solar tower system using the supercritical carbon dioxide cycle as the power cycle. The system was operated between 8 am and 4 pm. For a turbine inlet temperature of 600°C, a net power of 80 MW was obtained. It was also found that the highest exergy destruction was in the heliostat. Atif and Al-Sulaiman [17] performed the energy and exergy analysis of the solar tower-based supercritical carbon dioxide cycle. In the constant turbine inlet temperature, they obtained net power of 40 MW. In the plant, it was observed that the heliostat caused the highest exergy destruction. Moreover, today, Hybrid systems are being developed to meet energy demand via solar energy. Nafchi et al. [18] discussed a system including a solar tower and a hydrogen-fueled gas turbine. In the proposed system, the solar tower is caused the highest exergy destruction and cost. Boukelia et al. [19] proposed a new combined solar-assisted geothermal power plant and examined its thermodynamic performance. This power plant was compared with the conventional solar power plant and it was concluded that the proposed plant increased the thermodynamic performance by more than 30%. The solar tower was not only used for power generation. Li et al. [20] proposed a new combined heat and power system integrating a solar tower system with thermal energy storage and an absorption heat pump. With this system, 6214 kWh electrical energy and 14502 MJ thermal energy were produced. In the proposed system, the utilization efficiency of solar energy was obtained as 15.96%. In a study performed by Acar and Dincer [21], they examined the multiple production systems that could produce electricity, heat, air-conditioning, cooling and hot water. While the highest exergy efficiency of the system was found as 28%, the maximum electricity production was calculated as 550 kW. Colakoglu and Durmayaz [22] evaluated the energy and exergy analysis of a triple combined cycle including the solar tower. The energy and exergy efficiency of the proposed system were found to be 51.99% and 37.99%, respectively.

As seen above, although there are many studies on the solar tower, there are very few studies performed by depending on the thermodynamic analysis of the solar tower considering hourly wind speed, ambient temperature and solar energy per unit area. In addition, a few studies on solar tower design using the EBSILON®Professional simulation program in system design is executed.

This study is aimed to generate power by using the useful heat obtained from the solar tower, where the renewable energy source is used along with the steam Rankine cycle in the environmental conditions of the Iskenderun region of Hatay province. Firstly the wind speed, ambient temperature and DNI values that change throughout a day in June in Iskenderun for the installation of a solar power tower are determinated. Secondly the heat amount obtained from solar tower and efficiency of receiver is evaluated. Then According to the first and second laws of thermodynamics, the energy and exergy analysis of the proposed system is performed and the hourly thermodynamic performance of the system is performed for a day.

2. Material and Method

Today, the decrease in fossil-based resources and the deterioration in supply chains show how necessary the use of renewable energy is. These environmentally friendly sustainable systems are very important to choose the most suitable system according to the meteorological indicators of the area used. The fact that Iskenderun is one of the places with the highest solar radiation values brings the use of solar energy systems to the fore. In this study, a system that is powered by solar energy has been designed for the Iskenderun region, which is a region rich in terms of solar energy. The system consists of a solar power tower and a steam Rankine cycle. The schematic representation of the power system is given in Figure 1.

The radiation coming from the solar by means of the mirrors called heliostat is reflected to the receiver located on the top of the solar tower and then energy absorbed by the receiver is transferred to the working fluid in steam Rankine cycle. The working fluid, water, exits from the tower as superheated steam at 80 bar pressure and 950 °C, and the superheated steam is transmitted to the turbine. Here, the steam expands, and then mechanical power is generated. Meanwhile, the temperature of the fluid drops, and its pressure drops to 0.10 bar. The fluid pressure is increased to 80 bar again by using the pump and the working fluid is transferred to the tower. So the cycle is completed. (1→4).

The wind speed, ambient temperature and DNI values that change throughout a day in June in Iskenderun, which was chosen for the installation of a solar power tower, are given in Table 1. Wind speed varies between 2.14-5.39 m/s during the day. The ambient temperature increases towards noon and decreases towards evening. It reaches the highest ambient temperature of 30.79°C 12 pm. The DNI value shows a similar change to the ambient temperature. The DNI value, which is low in the morning hours, rises to 815.71 W/m2 at noon. Then, the DNI value decreases to 33.37 W/m2 until 18 pm.

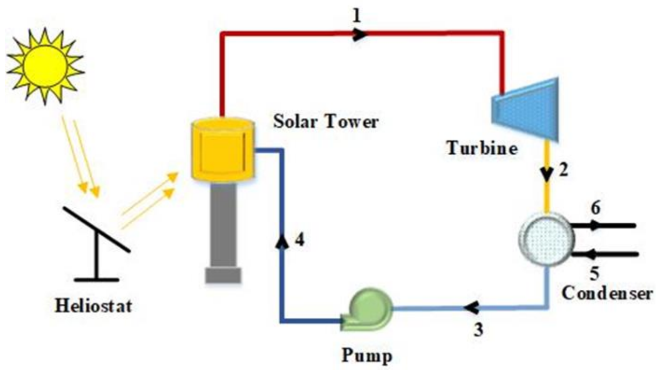

Fig. 1 Schematic representation of solar tower-assisted power generation system

Table 1. Changing wind speed, ambient temperature and DNI values of the Iskenderun region throughout the day [23]

Hours	Wind speed (m/s)	Ambient temperature (°C)	DNI (W/m²)
06:00	2.14	23.02	14.93
07:00	2.35	25.27	105.88
08:00	2.65	27.22	281.59
09:00	3.11	28.75	468.72
10:00	3.60	29.89	646.86
11:00	4.12	30.56	747.28
12:00	4.61	30.79	815.71
13:00	5.00	30.66	801.62
14:00	5.27	30.18	709.79
15:00	5.39	29.32	548.23
16:00	5.29	28.07	361.73
17:00	4.82	26.49	171.29
18:00	3.53	24.28	33.37

Thermodynamic analysis of the proposed solar energy-assisted power generation system is made. As a result of the analysis, the energy and exergy efficiencies of the system and the irreversibilities in the system are determined. The design parameters of the proposed system are given in Table 1.

While performing the thermodynamic analysis of the system, it is assumed that the system operates in a steady state, its kinetic and potential energies are neglected, and the turbines and pumps are adiabatic. In line with these assumptions, the mass, energy and exergy balances of the proposed system are respectively written as in Eq. (1), Eq. (2) and Eq. (3) [24,25].

Table 1. The design parameters of the proposed system

Parameter	Value
Ambient pressure, P_0	101.325 kPa
Working fluid	Water
Heliostat field, A_h	150000 m^2
Turbine inlet temperature	950 °C
Turbine inlet pressure	80 bar
Condenser pressure	0.10 bar
Coolant inlet temperature	10 °C
Coolant outlet temperature	31.81 °C

$$\sum \dot{m}_i = \sum \dot{m}_e \tag{1}$$
$$\sum \dot{Q}_i + \sum \dot{W}_i + \sum \dot{m}_i h_i = \sum \dot{Q}_e + \sum \dot{W}_e + \sum \dot{m}_e h_e \tag{2}$$
$$\sum \dot{Ex}_i^Q + \sum \dot{Ex}_i^W + \sum \dot{m}_i \psi_i = \sum \dot{Ex}_e^Q + \sum \dot{Ex}_e^W + \sum \dot{m}_e \psi_e + \dot{Ex}_{dest} \tag{3}$$

ψ, $\dot{Ex}^Q$ and $\dot{Ex}^W$ denote specific exergy, the exergy of heat, and work, respectively. The specific exergy, the exergy of heat and work are calculated with the formulas given in Eq. (4), Eq (5) and Eq. (6) [24]. The energy and exergy balance relations of each component of the system given in Figure 1 are given in Table 2.

$$\psi = (h - h_0) - T_0(s - s_0) \tag{4}$$
$$\dot{Ex}^Q = \left(1 - \frac{T_0}{T}\right)\dot{Q} \tag{5}$$
$$\dot{Ex}^W = W \tag{6}$$

Table 2. Energy and exergy balance relationships of each component in the proposed system [24-26]

Component	Energy and Exergy Balance Relationship
Solar tower	$\dot{m}_1 h_1 = \dot{Q}_{tower} + \dot{m}_4 h_4$ $\dot{m}_4 \psi_4 + \dot{Ex}_{tower}^Q = \dot{m}_1 \psi_1 + \dot{Ex}_{dest}$
Turbine	$\dot{m}_1 h_1 = \dot{m}_2 h_2 + \dot{W}_t$ $\dot{m}_1 \psi_1 = \dot{m}_2 \psi_2 + \dot{W}_t + \dot{Ex}_{dest}$
Condenser	$\dot{m}_2 h_2 + \dot{m}_5 h_5 = \dot{m}_3 h_3 + \dot{m}_6 h_6$ $\dot{m}_2 \psi_2 + \dot{m}_5 \psi_5 = \dot{m}_3 \psi_3 + \dot{m}_6 \psi_6 + \dot{Ex}_{dest}$
Pump	$\dot{m}_3 h_3 + \dot{W}_p = \dot{m}_4 h_4$ $\dot{m}_3 \psi_3 + \dot{W}_p = \dot{m}_4 \psi_4 + \dot{Ex}_{dest}$

The energy efficiency of the solar receiver and the exergy efficiency of the solar tower are given in Eq. (7) and Eq. (8), respectively.

$$\eta_{I,rec} = \frac{\dot{Q}_{rec,i} - \dot{Q}_{rec,loss}}{\dot{Q}_{rec,i}} \tag{7}$$
$$\eta_{II,rec} = \frac{\dot{m}_1 \psi_1 - \dot{m}_4 \psi_4}{\dot{Ex}_{tower}^Q} \tag{8}$$

$\dot{Ex}_{tower}^Q$ is found by Eq. (9).

$$\dot{Ex}^{Q}_{tower} = \left(1 - \frac{T_0}{T_{surface}}\right) \dot{Q}_{rec,i} \quad (9)$$

Here, $T_{surface}$ is the average temperature of the fluid entering and leaving the receiver. $\dot{W}_{net}$ refers to the net power produced by the solar power tower and it is calculated with the formula given in Eq. (10). The energy and exergy efficiencies of the proposed solar power tower are obtained using Eq. (11) and Eq. (12).

$$\dot{W}_{net} = \dot{W}_t - \dot{W}_p \quad (10)$$

$$\eta_I = \frac{\dot{W}_{net}}{\dot{m}_1 h_1 - \dot{m}_4 h_4} \quad (11)$$

$$\eta_{II} = \frac{\dot{W}_{net}}{\dot{m}_1 \psi_1 - \dot{m}_4 \psi_4} \quad (12)$$

3. Results and Discussions

When the climatic conditions of Iskenderun are examined, it is seen that Iskenderun is a suitable region for solar energy and electricity generation systems. In the study, a solar power tower system is proposed for the Iskenderun region and a thermodynamic analysis is made. The power plant works with solar energy during daylight hours. By entering parameters of the wind, DNI and the ambient temperature into the EBSILON®Professional simulation program, the heat entering the receiver, the heat output and the receiver losses are calculated. Also, the flow rate of the working fluid was changed throughout the day and thus the outlet temperature of the receiver was kept constant at 950 °C. In this way, the heat obtained from the system was also increased. Firstly, the analysis of the solar tower is carried out. The heat coming to the receiver from the solar and receiver losses, which change throughout the day, have been determined and their changes are shown in Figure 2.

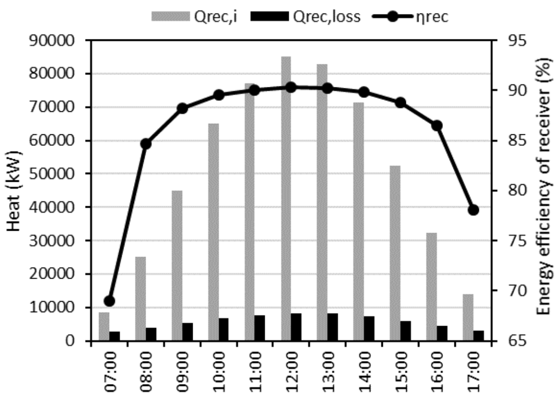

Fig. 2 The change of heat entering the receiver, receiver loss and efficiency during the day

The lowest heat coming to the receiver and minimum heat loss resulting from receiver is performed at 07:00 in the morning. The highest heat from the solar reaches the receiver at 12 pm as 85.04 MW. The heat loss in the receiver is 8.26 MW. The energy efficiency of the tower is found from the values of heat entering the receiver and receiver losses. The highest and lowest energy efficiency of the receiver is found as 90.29% and 69.02%, respectively. It is observed that the energy efficiency of the receiver increased when the DNI is high. The change in exergy efficiency of the tower during the day is shown Figure 3.

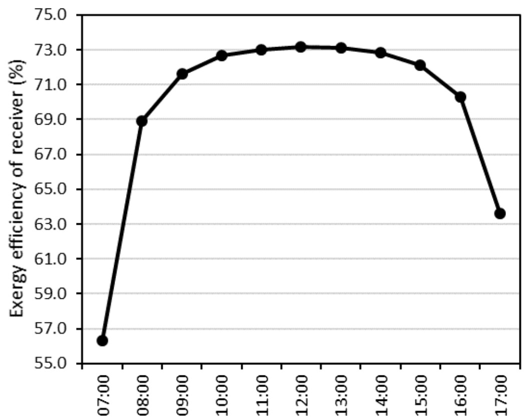

Fig. 3 The change in exergy efficiency of the receiver during the day

As seen in Figure 3, it is observed that the exergy efficiency of the receiver decreases during the low hours of the DNI value and increases during the high hours. When the DNI is 105.88 W/m^2, the exergy efficiency is 55.60% at 07:00. The DNI value increases to 815.71 W/m^2 at 12 pm. The exergy efficiency of the tower increases to 72.13% with this increase. Exergy efficiency decreases towards evening hours again. It is found that the exergy efficiency of the receiver varies inversely with the energy efficiency. The variation of the mass flow rate of the working fluid in the solar power tower system between 06:00 and 18:00 is given in Figure 4.

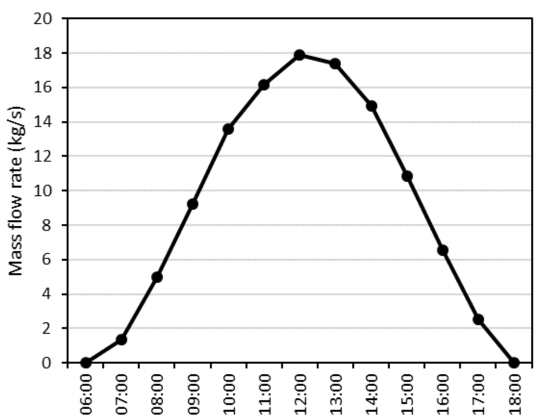

Fig. 4 The change of the mass flow rate of the working fluid during the day

While the mass flow rate of the water increases towards the noon hours, it decreases towards the evening hours. The mass flow rate is highest at 12 pm and is founded as 17.89 kg/s. The variation of the heat value entering the steam Rankine cycle from the tower during the day and the DNI are given in Figure 5.

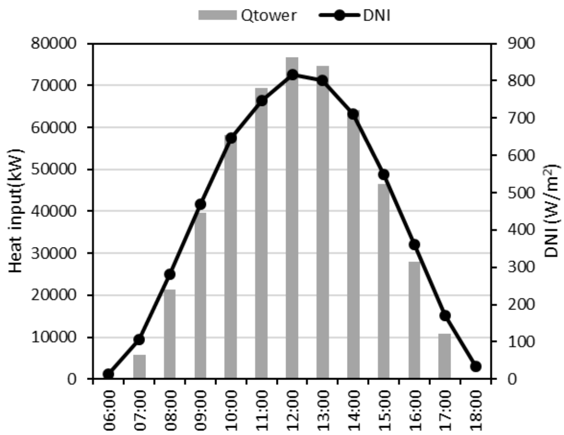

Fig. 5 The changing in the values of heat entering the solar power tower and DNI during the day

While the DNI values are 105.88 W/m^2 and 171.29 W/m^2, the heat inputs are found to be 5893 kW and 10778 kW, respectively. It is calculated as 76778 kW for the highest DNI value. While the DNI value is 801.62 W/m^2 at 13:00, 74636 kW of heat entered the tower. The heat input increases proportionally with the DNI value. The power generated from the turbine with the heat entering during the day and the net power are given in Figure 6.

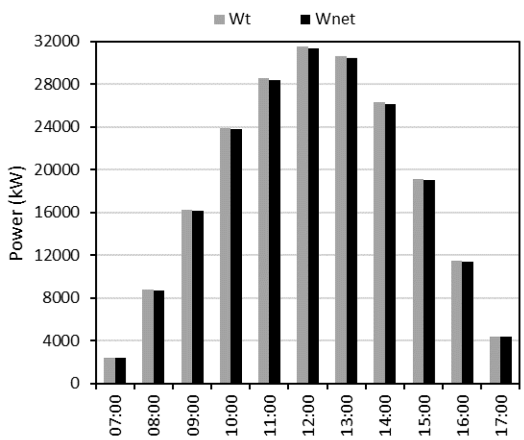

Fig. 6 The change of the power generated in the turbine and the net power in the solar power tower system during the day

Power production of 28539.8 kW, 31552.5 kW and 30672.3 kW were obtained from the turbine at 11:00, 12:00 and 13:00, respectively. The net power produced is 28366.2 kW, 31360.6 kW and 30485.8 kW, respectively. The lowest net power in the system is calculated as 2406.3 kW in the DNI value of 105.88 W/m^2. Total heat of 495.3 MWh/day enters the tower throughout the day. A power of 202.3 MWh/day was produced with this heat input. The change of exergy destruction occurring in the system and the component of the system during the day is given in Figure 7.

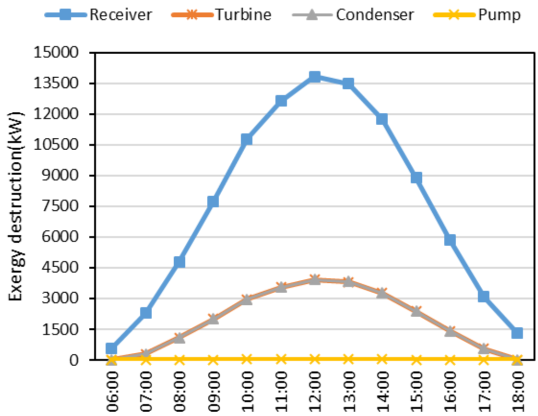

Fig. 7 The variation of exergy destruction in the overall system and its components during the day

The exergy destruction of all components increases during the hours when the value of DNI and ambient temperature are high. The exergy destruction of the tower, turbine, condenser and pump at 12 pm is calculated as 13.83 MW, 3.93 MW, 3.93 MW and 36.81 kW, respectively. The highest exergy destruction occurred in the tower. The values of exergy destruction occurring in the turbine and condenser during the day are close. The lowest exergy destruction occurred in the pump. A similar change to the ambient temperature occurred in the component. The changing in the energy and exergy efficiency of the solar power tower system throughout the day is given in Figure 8.

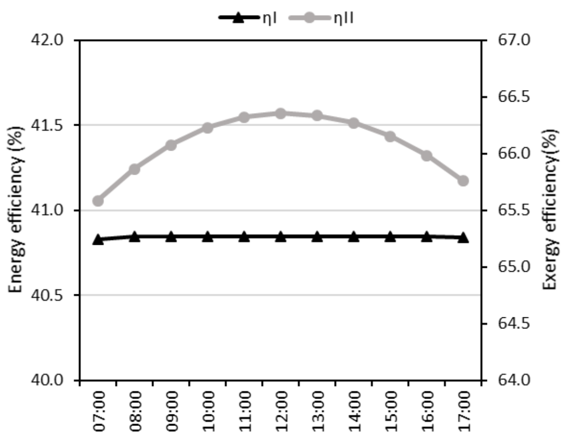

Fig. 8 The changing in the energy and exergy efficiency of the solar power tower system throughout the day

As can be seen in Figure 8, the average daily energy efficiency of the solar power tower system is around 40.8%. There is no significant change in the energy efficiency of the system during the day. The exergy efficiency varies between 65.6% and 66.35%. The ambient temperature changing during the day causes a change in the exergy efficiency. The high ambient temperature increases the exergy efficiency. Therefore, the highest exergy efficiency is reached at 12 pm. The average exergy efficiency of the system is obtained as 66.08%. Dunham et al. analyzed steam Rankine cycle that operates at the 20 MPa and 1100

°C. Correspondingly, they appeared that efficiency of system is about 45% [27]. Besides, Zhang et al evaluated the steam Rankine cycle that has 38 MPa and 700 °C. They asserted that efficiency of the proposed system is calculated as about 51% [28]. Xu et al. [5] investigated the effect of DNI on energy efficiency. They stated that if the DNI value increases from 100 W/m^2 to 1000 W/m^2, the efficiency of the solar receiver also increases from about 45% to 90%. They found that the solar system has the highest exergy destruction. 550 °C of turbine inlet temperature, the efficiency of the power cycle was calculated as 37.5%. Similar results with the literature were obtained. In the studies in the literature, solar power tower systems were made for a certain DNI value. There are not many studies examining the effect of climatic conditions on the performance of that region for a particular region. The proposed system does not harm the environment and it has been found to be good in terms of performance when installed in a region rich in solar energy such as İskenderun. The thermodynamic properties of the fluid at each state in the system are given in Table 3.

Table 3. The state points of the solar power tower system

State	Pressure (bar)	Temperature (°C)	Enthalpy (kJ/kg)	Density (kg/m^3)	Volume flow rate (m^3/s)	Entropy (kJ/kgK)	Exergy (kJ/kg)
1	80.00	950.00	4,493.77	14.27	1.25	7.8410	2,117.53
2	0.10	120.56	2,726.65	0.06	324.74	8.5511	134.58
3	0.10	45.81	191.81	989.84	0.02	0.6492	1.41
4	85.00	46.60	202.51	993.17	0.02	0.6559	10.08
5	2.00	10.00	42.21	999.75	0.50	0.1511	3.22
6	1.95	31.81	133.47	995.13	0.50	0.4616	0.10

4. Conclusions

The use of solar energy, one of the renewable energy sources, is increasing day by day to meet the energy demand increases. In the study, it is integrated with the current steam Rankine cycle and the maximum potential energy production of the proposed system for the region where the solar energy potential is high was evaluated. Iskenderun of Turkey, which has a high solar energy potential is selected as region and the solar power tower system was investigated by performing energy and exergy analysis. Values such as wind speed, ambient temperature and DNI change during the day. In the case of the installation of this Integrated system in the Iskenderun region, the losses occurring in the receiver, the effect of these changing values on the receiver efficiency and system performance have been examined. As a result of the analysis, the following findings are obtained:

- The heat entering the receiver and the receiver losses are shown similar changes with the DNI value. High heat input and receiver efficiency are obtained during the hours when the DNI value was high. The highest receiver efficiency is found to be 90.29%.
- The exergy efficiency of the receiver in the system increases with the increase of the value of DNI. The heat entering the steam Rankine cycle from the solar tower increases with the increase of this value. The heat input is found to be 76,778 kW for the highest DNI value of 815.71 W/m^2. The high heat input increased the net power produced in the steam Rankine cycle. The solar tower received 495.3 MW of heat throughout the day and generated 202.3 MW of net power.
- The highest exergy destruction in the system was caused by the solar tower. The highest exergy destruction of the solar tower, turbine, condenser and pump

occurred at 12 pm and it is calculated that it was 13.83 MW, 3.93 MW, 3.93 MW and 36.81 kW, respectively.

- The average daily energy and exergy efficiencies of the solar power tower system are around 40.8% and 66.08%, respectively. It is concluded that the exergy efficiency varies similarly with the ambient temperature during the day.

In addition, the installation of a renewable energy integrated power system in the current study will reduce both greenhouse gas emissions and external dependence on energy. In addition to these, the economic dimension of the implementation of the system should also be investigated.

Symbols

h	Specific enthalpy [kJ/kg]
s	Entropy [kJ/kgK]
P	Pressure [kPa]
T	Temperature [K]
$\dot{m}$	Mass flow rate [kg/s]
$\dot{Q}$	Heat flow rate [kW]
$\dot{W}$	Power [kW]
η	Efficiency [%]
ψ	Specific exergy [kJ/kg]
DNI	Direct normal irradiance [W/m^2]

Subscripts

I	energy
II	exergy
e	exit
i	inlet
$dest$	destruction
p	pump
rec	receiver
t	turbine
0	ambient temperature

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