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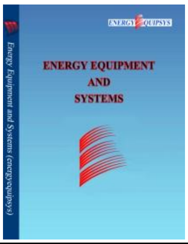

A thermodynamic model for exergetic performance and optimization of a solar and biomass-fuelled multigeneration system

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ABSTRACT

Integrated energy systems utilizing renewable sources are sustainable and environmentally substitutes for conventional fossil-fired energy systems. A new multigeneration plant with two inputs, such as biomass and solar energy, and four useful outputs, such as cooling, heating, power, and distilled water, is presented and investigated in this paper. The proposed system includes evacuated tube solar collectors, biomass burners, the organic rankine cycle (ORC), absorption chillers, heaters, and a multi-effect desalination system (MED). The results showed that the proposed system can produce 802.5 kW for power, 10391 kW for heating, 5658 kW for cooling, and 9.328 kg/s for distilled water. The energy efficiency of the system is 61%, while the exergy efficiency is 7% and the main sources of exergy destructions are biomass burner, evacuated tube solar collectors, and the vapour generator. Exergy optimization is carried out to find the optimum point of the system.

Keywords: Multigeneration, Desalination, Optimization, Solar Energy, Biomass.

1. Introduction

Increasing world population and demand for energy as well as potable water are leading to burning of more fossil fuels, thereby releasing large amounts of greenhouse gases, particularly carbon dioxide. In order to reduce CO_2 emission by using renewable energy instead of fossil fuels is the main challenge for sustainable development. Issues like fossil fuel depletion and climate change boost the advantages and significance of efficient multigeneration energy systems [1]. The multigeneration system is a kind of cogeneration system with more than three outputs, namely power, heating, cooling, and fresh water. Dincer and Zamfirescu [2] showed that multigeneration systems based on renewable energies, such as clean and free alternatives of fossil fuels, reduce fuel prices and emissions compared to conventional systems like cogeneration or trigeneration systems.

Other studies show that the exergy efficiency of multigeneration systems increases up to 10% by using an ORC with renewable energy sources, and integration of two renewable energy sources, such as biomass and solar energy, can be beneficial with higher energy and exergy efficiency than a single renewable energy source [3, 4]. Dincer et al. [5] showed that a multigeneration renewable energy-based system has better efficiency, sustainability, and environment. Rubio-Mayaet et al. [6] designed a multigeneration system fuelled by natural gas, solar, and gasified biomass, concluding that renewable energy is the source of the reduction

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of CO_2 and environmental impact. Minciuc et al. [7] offered an approach for investigating the multigeneration system and reported the optimal energetic efficiency of the system. Ahmadi et al. [8] presented an exergy-based optimization of a multigeneration energy system to produce power, heating, cooling, and domestic hot water. They found the best design parameters of the system by considering exergy efficiency as an objective function. Zamfirescu et al. [9] examined the multigeneration system as a method of improving the exergy efficiency of the nuclear power system. Ratlamwala et al. [10] analyzed the performance of a novel integrated geothermal-based system for multigeneration for producing cooling, heating, power generation, hot water, and hydrogen. Ozlu and Dincer [11] developed a solar-wind hybrid multigeneration system, and analyzed the energy and exergy efficiency of the system, both higher than equivalent single energy system's efficiencies. Solar energy can be collected through many methods such as evacuated tube solar collectors (ETC), which are used in this study. Biomass is often derived from living or dead matter present on earth. Bagasse is a kind of biomass that is selected as one of the energy sources for the studied system. Biomass fuels can be obtained from agricultural production wastes especially sugarcane. J. Werther et al. [12] studied the processes of different agricultural wastes combustion including sugarcane. L.A.B Cortez et al. [13] performed an exergy analysis so as to use its heat in bagasse combustion. A. Bhattacharja et al. [14] studied and researched on the power generation process by utilizing the bagasse gas-integrating system in terms of energy and exergy. But a multigeneration plant driven by solar energy and bagasse combustion and generating electric power, cooling power, heating power, and desalinated water, has not been analyzed from the viewpoint of thermodynamics. In this paper, the energy and exergy analysis of a multigeneration plant driven by bagasse combustion and solar energy is investigated. Sensitivity analysis is carried out in order to observe the effect of design parameters on system performance. The optimization of the proposed system is performed through EES software, and the optimum point of system is determined considering the exergy efficiency as an objective function.

Nomenclature

A_{coll}	Solar collector area (m^2)
Ex	Specific exergy (kJ/kg)
$\dot{Ex}$	Exergy (kW)
G_t	Total instantaneous radiation, W/m^2
h	Specific enthalpy (kJ/kg)
i	Inlet
$\dot{m}$	Mass flow rate (kg/s)
e	Outlet
P	Pressure
$\dot{Q}$	Heat transfer rate (kW)
R	Gas constant (kJ/kg K)
s	Specific Entropy (kJ/kg.K)
T	Temperature (°C)
$\dot{W}$	Power (kW)
x_k	Number of molecules of gas k (molecules)

Subscripts

0	Ambient
ch	Chemical
D	Destruction
elec	Electrical
Eva	Evaporator
Gen	Generator
HHV	High Heating Value
ph	Physical
Turb	Turbine

Greek symbols

ε	Exergy efficiency

Abbreviation

EES	Engineering Equation Solver
ORC	Organic Rankine Cycle

2.System Description

Figure 1 shows the schematic of the suggested multigeneration system, which can be divided into the evacuated tube collector (ETC), the biomass burner, and the organic rankine cycle (ORC), the absorption chiller, the heater, and the multi-effect desalination system (MED). The outputs of the proposed system are electricity, heating, cooling, and fresh water. The suggested system is based on two renewable energy sources: solar energy, which is the solar radiation collected through the ETC, and bagasse, which is combusted into a biomass burner.

Hot combustion gases pass through the vapour generator and enter into a single-effect absorption cycle that uses LiBr-H_2O to provide cooling. In the ORC, the heat released from the biomass burner is transferred to R123 and make a superheated vapour for producing power in the ORC turbine. The wasted energy of turbine is used by a heater to provide heating. In Heat Exchanger 2 the remaining heat is transferred to seawater for preheat purposes, and R123 enters into the vapour generator to complete the cycle. The last purpose of this system is to produce fresh water by a MED, which contains four effects. As sufficient and low-cost heating can be provided in this system, MED is best option compare to any other types of desalination plant. Seawater enters into the first effect after preheating, and a part of it is converted to fresh water. In each effect, pure water is produced at lower pressure and lower temperature than the previous effect. The produced vapour of each effect feeds as the heating steam for the next effect and so on. The feed water passes through the preheater and enters into the ETC and then the produced steam therein enters into the ejector. By increasing the inlet steam pressure, the ejector provides an appropriate pressure for the first effect of MED entrance. Data has been collected from Khuzestan province, Iran. This province is among the most effective areas in Iran for exploitation of solar energy, as it enjoys more than 300 sunny days; there are 86,588 hectares under cultivation and about 6,536,976 tons of the total produce are attained from nine large sugar production factories [15].

3.Thermodynamic Analysis

In this section, a thermodynamic analysis, including the energy and exergy analysis, is carried out by using the following assumptions:

- The reference-environment state has a temperature $T_0 = 298$ K and a pressure $P_0 = 100$ kPa.
- The changes in kinetic, and potential energy and exergy terms are negligible.
- HHV for bagasse is 16,793 kJ/kg [13].
- The higher heating value (HHV) is the primary contributor to the chemical exergy of a biomass fuel and obtained from the below equation [16]:

$$\frac{e_f^{-ch}}{HHV} \approx 1.00 - 1.04$$

Energy balance is applied for each component of the system in order to determine the thermodynamic properties of the working fluid in different states [17]:

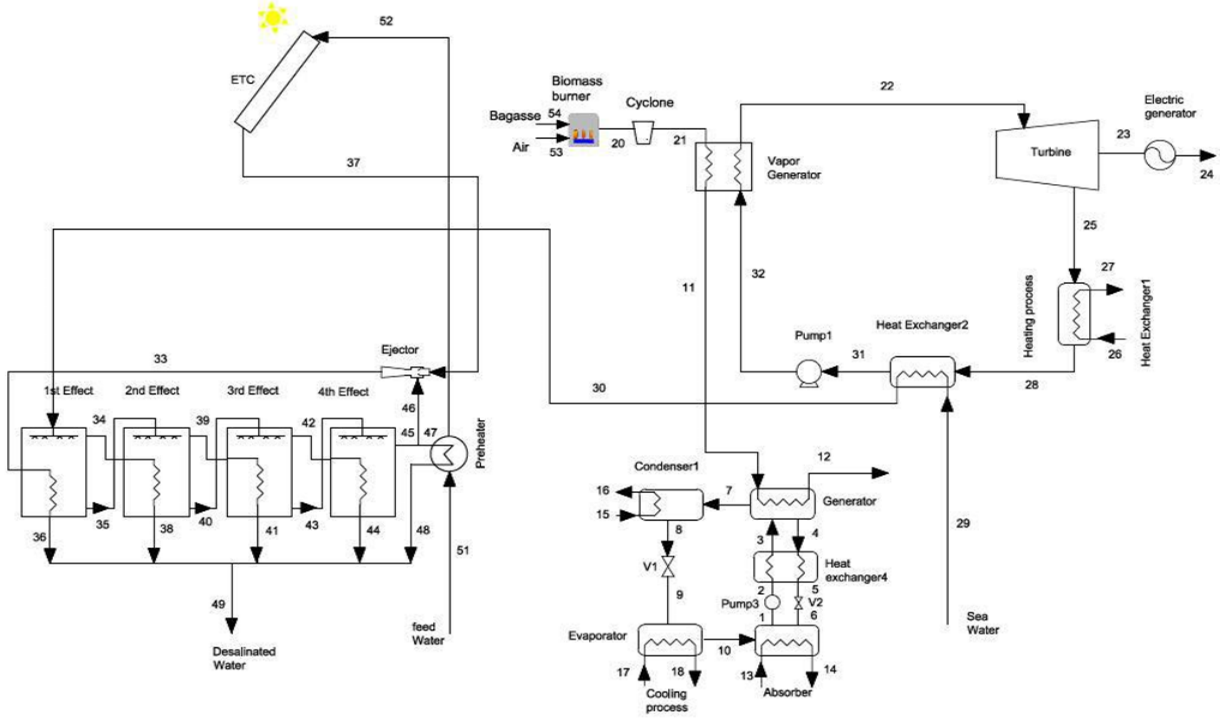

Fig. 1. Schematic of the proposed multigeneration system

$$\sum \dot{m}_i = \sum \dot{m}_e \tag{1}$$

$$\sum \dot{Q} - \sum \dot{W} = \sum \dot{m}_e h_e - \sum \dot{m}_i h_i \tag{2}$$

The bagasse combustion equation based on wet analysis is as following [14]:

$$\begin{aligned} &0.268C + 0.239H_2 + 0.099O_2 \\ &\qquad + 0.394H_2O + Ash] \\ &+[1.075N_2 + 0.289O_2 + 0.013Ar] \\ &\rightarrow [0.268CO_2 + 0.633H_2O \\ &\qquad + 1.075N_2 \\ &\qquad + 0.013Ar] \end{aligned} \tag{3}$$

Whenever any irreversibility occurs, exergy is destroyed. Exergy analysis is an applicable tool to identify the location and causes of thermodynamic destructions; it helps engineers to improve and optimize the system operation. The exergy of a substance is often divided into four components: physical and chemical exergy being the common ones and kinetic and potential exergy being negligible in this context. Exergy balance for a control volume in a steady state process is as follows [17]:

$$E\dot{x}_Q + \sum_i \dot{m}_i ex_i = \sum_e \dot{m}_e ex_e + E\dot{x}_W + E\dot{x}_D \tag{4}$$

$$ex_{ph} = (h - h_0) - T_0(s - s_0) \tag{5}$$

$$ex_{ch} = \sum x_k ex_{ch}^k + RT_0 \sum x_k \ln x_k \tag{6}$$

By regarding the non-conservation law for entropy, exergy balances are applied for each component of the multigeneration system and are listed in Table 1.

Energy and exergy analysis, based on the first and second laws of thermodynamics, are two alternatives for evaluating the

Table 1. Exergy destruction rate and exergy efficiency of system components

Component	Exergy destruction rate ($E\dot{x}_D$)	Exergy efficiency (ε)
Turbine	$\dot{m}[22]\times(ex[22]-ex[25])-\dot{W}_{turb}$	$1-\frac{\dot{W}_{turb}}{\dot{m}[22]\times(ex[22]-ex[25])}$
Heat Exchanger1	$\dot{m}[25]\times(ex[25]-ex[28])-\dot{m}[26]\times(ex[27]-ex[26])$	$1-\frac{\dot{m}[26]\times(ex[27]-ex[26])}{\dot{m}[25]\times(ex[25]-ex[28]}$
Pump	$\dot{W}_{pump_1}-\dot{m}[31]\times(ex[32]-ex[31])$	$1-\frac{\dot{m}[31]\times(ex[32]-ex[31])}{\dot{W}_{pump_1}}$
Preheater	$\dot{m}[47]\times(ex[47]-ex[48])-\dot{m}[50]\times(ex[51]-ex[50])$	$1-\frac{\dot{m}[50]\times(ex[51]-ex[50])}{\dot{m}[47]\times(ex[47]-ex[48])}$
Collector	$E\dot{x}_s-\dot{m}[51]\times(ex[37]-ex[51])$	$1-\left(\frac{\dot{m}[51]\times(ex[37]-ex[51])}{E\dot{x}_s}\right)$
Ejector	$(\dot{m}[37]\times ex[37])+(\dot{m}[46]\times ex[46])-(\dot{m}[33]\times ex[33])$	$1-(\frac{\dot{m}[46]\times(ex[33]-ex[46])}{\dot{m}[37]\times(ex[37]-ex[33])})$
Absorber	$\dot{m}[10]\times ex[10]+\dot{m}[6]\times ex[6]-\dot{m}[1]\times ex[1]+\dot{m}[13]\times(ex[14]-ex[13])$	$1-(\frac{\dot{m}[1]\times ex[1]+\dot{m}[13]\times(ex[14]-ex[13])}{\dot{m}[10]\times ex[10]+\dot{m}[6]\times ex[6]})$
Evaporator	$\dot{m}[9]\times(ex[9]-ex[10])-\dot{m}[10]\times(h[10]-h[9])\times(1-(\frac{T_0+273}{T_{eva}+273}))$	$1-(\frac{\dot{m}[10]\times(h[10]-h[9])\times(1-(\frac{T_0+273}{T_{eva}+273}))}{\dot{m}[9]\times(ex[9]-ex[10])})$

performance of the system. Energy analysis is unable to express the irreversibility, but exergy analysis is capable of overcoming the shortcomings of the energy analysis. Energy and exergy efficiencies for the multigeneration system are stated as follows:

$$\eta = \frac{\dot{W}_{elec} + \dot{Q}_{cooling} + \dot{Q}_{heating} + (\dot{m}_{49}h_{49} - \dot{m}_{29}h_{29})}{A_{coll} \times G_t + \dot{m}_{54} \times HHV_{bagasse}} \quad (7)$$

$$\varepsilon = \frac{\dot{W}_{elec} + E\dot{x}_{cooling} + E\dot{x}_{heating} + (\dot{m}_{49}ex_{49} - \dot{m}_{29}ex_{29})}{E\dot{x}_s + (\dot{m}_{54} \times ex_{bagasse})} \quad (8)$$

where the exergy of bagasse is taken to be 16,793kJ/kg [16], and the amount of exergy of the sun can be calculated from following equation [18–21]:

$$E\dot{x}_s = A_{coll} \times G_t \times \left[1 + \frac{1}{3}\left(\frac{T_0}{T_s}\right)^4 - \frac{4}{3}\left(\frac{T_0}{T_s}\right)\right] \quad (9)$$

in which T_S is the sun temperature and is equal to 6000 k.

4.Results And Discussion

In this section, thermodynamic modeling is implemented by applying the mentioned equations through the Engineering Equation Software (EES) [22] and using input data shown in Table 2. The result of the thermodynamic modeling of the multigeneration system is presented in Table 3. The system is proposed for locating in Ahwaz, Iran. Since it has sufficient sources of bagasse and solar radiation. The average daily solar radiation is extracted from the NASA internet site [23].

Table2. Input data for thermodynamic modelling

Parameter	Value
Turbine inlet temperature	130 ^{0}C
Turbine inlet pressure	700 kPa
Turbine pressure ratio	2.5
Heat exchanger temperature difference	10 ^{0}C
Temperature difference of each effect of MED	5 ^{0}C
Evaporation temperature	1.5 ^{0}C
Condenser temperature difference	5 ^{0}C

Based on the achieved data, the performance of the system is evaluated and presented in Table 4.

Table 4. Performance of the system

Parameters	Values
Thermal efficiency	61 %
Exergy efficiency	7%
Cooling load	5658 KW
Heating load	10391 KW
Power	802.5 KW
Fresh water	9.328 Kg/s

Figure 2 shows the amount of exergy destruction for some components of the system that has a considerable share in the total exergy destruction of the system in comparison with others. As it is shown, the biomass burner (21539KW), ETC (9829KW), and vapour generator (741.7 KW) are the major sources of the exergy destruction rate. In the biomass burner, the irreversibility is attributable to occurrence of combustion in it since the combustion process is one of the major sources of irreversibility. In the ETC, such irreversibility is created due to large temperature differences between solar heat and fluid in the tubes. The main reason of irreversibility in the vapour generator is related to stream-to-stream heat transfer. Since the amount of irreversibility of remaining components is negligible, their exergy destruction is not considered here.

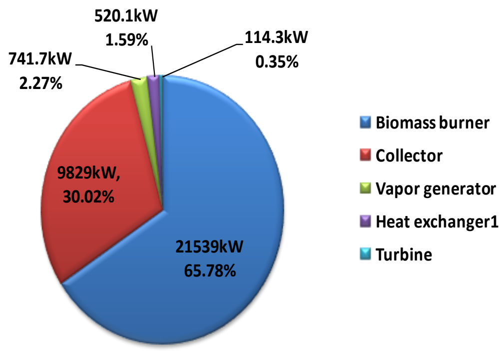

Fig. 2. Exergy destruction rate of components of multigeneration system

Three independent variables, including turbine inlet temperature, turbine inlet pressure, and Heat Exchanger1 temperature difference, are varied to investigate their effects on the exergy efficiency of the multigeneration system. This is illustrated in Fig.s 3, 4, and 5. Figure 3 demonstrates the effect of turbine inlet temperature on the exergy efficiency of the system by increasing

Table3. Result of thermodynamic modelling for the proposed system

Stream	$T(°C)$	$P(kPa)$	$h(kJ/kg)$	$h(kJ/kg.K)$	$\dot{Ex}(kW)$
1	34.6	0.6812	93.07	0.1977	283.6
2	34.6	7.424	97.19	0.1977	287.7
3	67.6	7.424	159	0.3989	289.5
4	80	7.424	185.6	0.4665	553.3
5	45.62	7.424	123.2	0.264	551.3
6	35.62	0.6812	123.2	0.202	569.7
7	80	7.424	2649	8.481	126.6
8	40.11	7.424	168	0.5737	1.486
9	1.5	0.6812	168	0.6116	9.795
10	1.5	0.6812	2503	9.114	208.3
11	87.25	101.3	361.2	5.886	5.729
12	25	101.3	298.6	5.695	0.0211
13	35	101.3	146.7	0.5049	-
14	25	101.3	104.8	0.3669	-
15	25	101.3	104.8	0.3669	-
16	30	100	125.8	0.4365	-
21	150	101.3	424.8	6.049	-
22	130	700	470.8	1.772	41.92
25	105	280	455.5	1.779	24.47
26	29.93	150	125.5	0.4355	1394
27	59.93	150	251	0.8302	1402
28	59.23	280	262.5	1.206	2.222
29	25	101.3	99.01	0.3459	0
30	49.23	101.3	195.4	0.657	3.682
31	35	280	236.7	1.125	0.3335
32	35.28	700	237.1	1.126	0.6306
33	133.3	297.9	2725	6.994	645.1
34	99.86	100.8	2675	7.356	487.8
35	99.05	101.3	388.9	1.21	31.27
36	133.3	297.9	560.6	1.67	67.55
37	138.9	350	2732	6.939	668.3
38	99.86	100.8	418.5	1.305	33.99
39	99.72	100.3	2675	7.358	487.1
40	98.63	101.3	379.6	1.175	30.91
41	99.72	100.3	417.9	1.304	33.87
42	99.58	99.8	2675	7.36	486.4
43	98.1	101.3	367.7	-	30.83
44	99.58	99.8	417.3	1.302	33.75
45	99.44	99.3	2675	7.361	485.7
46	99.44	99.3	2675	7.361	485.7
47	99.44	99.3	2675	7.361	485.7
48	99.44	99.3	2227	6.16	396.1
50	25	350	105.1	0.3669	0.2494
51	89.44	350	374.8	1.186	25.91
52	25	101.3	104.8	0.3669	-

the turbine inlet temperature between 110º C and 140º C. This prompts the exergy efficiency to increase about 1.6%. By increasing the inlet temperature of the turbine, more electricity is produced and hence the exergy efficiency increases too.

The effect of variation of turbine inlet pressure on the exergy efficiency of the system is shown in Fig.4. As turbine inlet pressure varies between 650 kPa and 800 kPa, the exergy efficiency of the system decreases about 0.5% due to decrement of the amount of electricity and heating power produced by the multigeneration system.

Figure 5 represents the effect of Heat Exchanger 1 temperature difference on the exergy efficiency of the system. It can be observed by increasing Heat Exchanger1 temperature difference between 5 and 15, as the exergy efficiency of the system decreases. This is because of decrement in the exergy produced by Heat Exchanger 1.

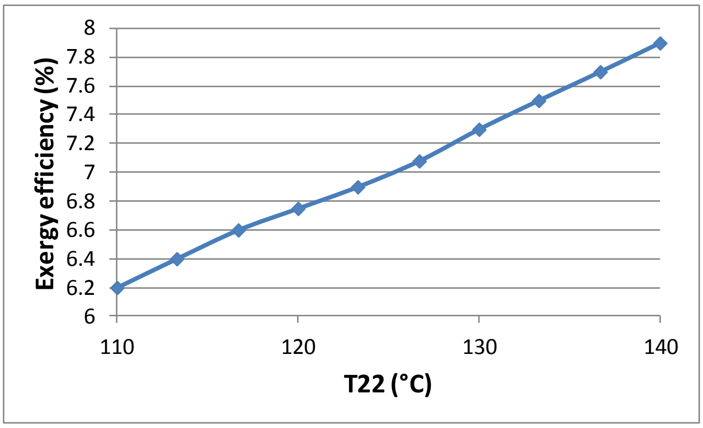

Fig. 3. Effect of turbine inlet temperature on exergy efficiency

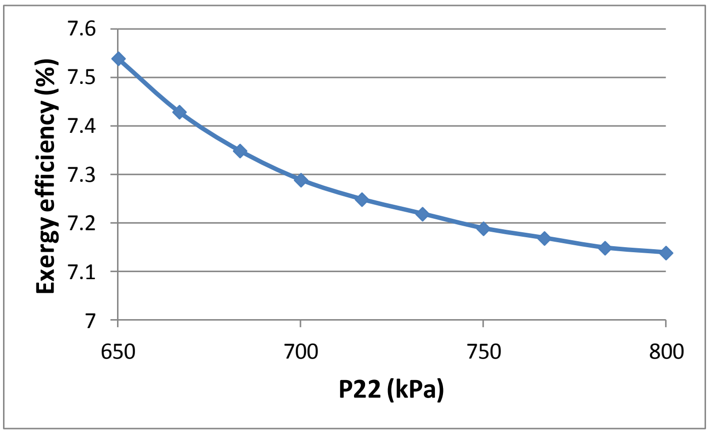

Fig. 4. Effect of turbine inlet pressure on exergy efficiency

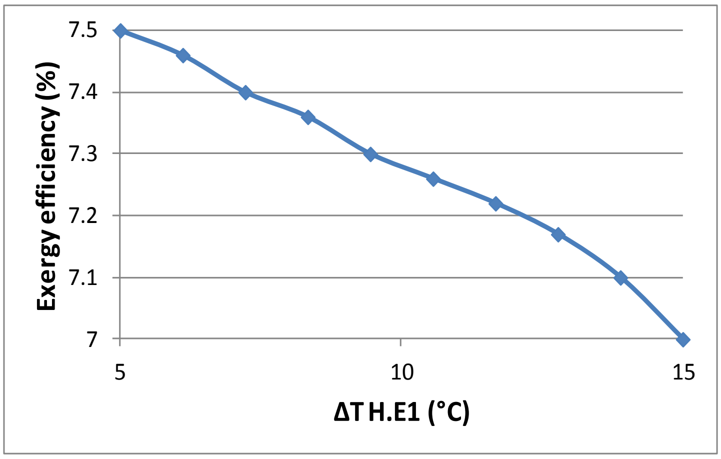

Fig. 5. Effect of temperature difference of Heat Exchanger 1 on exergy efficiency

5.Optimization

Optimization is a powerful tool that helps engineers to determine the best design parameters of the system regarding the existing constraints. To formulate an optimization problem, it is required to define the optimization method, objective functions, and constraints [24]. For this purpose, a genetic algorithm (GA) through the EES software is used for the optimization of the proposed multigeneration plant. GA is based on the biological genetic progress theory and was introduced by John Holland for the first time [25]. Exergy efficiency, as defined in Equation (9), is selected as the objective function, which is to be maximized. The selected decision variables are turbine inlet temperature (T[22]), turbine inlet pressure (P[22]), and the temperature difference of Heat Exchanger 1(ΔT_{HE1}). The constraints related to these parameters are shown in Table 5. By applying GA and using the constraints and objective function, the optimization is carried out, and the results are shown in Table 6.

In Table 6, the base case and optimal case values of the decision variables and objective functions are shown for better comparison. As shown in Table 6, exergy efficiency increases 1.5% in comparison with the base case value.

6.Conclusion

The present study proposes a biomass and solar-based multigeneration system that generates electricity, cooling power, heating power, and fresh water. Energy and exergy analysis is applied to identify the components with a high exergy destruction rate and to calculate the exergy efficiency of the system. The results show that biomass burners, evacuated tube solar collectors, and the vapor generator are the major sources ofexergy destruction. Hence, it is necessary to have a better design for these components to minimize the system exergy destruction. By increasing the turbine inlet temperature, decreasing the turbine inlet pressure, and decreasing the temperature difference of Heat Exchanger 1, the exergetic performance of the system improves. The energy and exergy efficiencies for the suggested system are calculated to be 61% and 7%, respectively. The optimization is carried out through the EES software by using GA, and the results show that exergy efficiency in the optimum case improves 1.5% in comparison with the base case value.

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Table 5. Constraints of decision variables

$$110°C < T_{22} < 140°C$$

$$650kPa < P_{22} < 800kPa$$

$$5°C < \Delta T_{H.E1} < 15°C$$

Table 6. Base case and optimal case values of the decision variables and objective functions

Parameters	Base case	Optimal case
Exergy efficiency (%)	7	8.5
Turbine inlet pressure (kPa)	700	657.5
Turbine inlet temperature (oC)	130	137
Temperature difference of Heat Exchanger 1 (oC)	10	5

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