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Thermodynamic Assessment of an Integrated Solar-Biomass System for Quadruple Generation Purposes

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A B S T R A C T

In this paper, a new quadruple generation plant with biomass and solar energy as input and four useful outputs, such as hydrogen, heating, power, and hot water is analysed from thermodynamic point of view. The proposed system includes parabolic solar collectors (PTC), biomass burners, the Rankine cycle (SRC), domestic water heater (DWH) and proton exchange membrane (PEM). The results showed that the energy efficiency of the system is 58.24% while the exergy efficiency is 51.68% and the main sources of exergy destructions are biomass burner, solar collectors, and electrolyzer.

1. Introduction

Nowadays, meeting to growing population, demands for energy and water has been increased. Using fossil fuels as common energy sources lead to Greenhouse Gases (GHG) emission and global warming issue. To avoid environmental pollution and because of fossil fuels depletion, focus on using renewable energy sources as free and clean alternatives for common energy sources is increased. Natural energy sources such as solar, wind, geothermal, biomass and tidal energy are treated as renewable and non-emission energy sources. In addition to, designing renewable based systems with higher efficiency and more sustainability is an important goal for researchers. Polygeneration energy systems with one or more energy sources have multiple products like power, heating, cooling, hydrogen, heating water and air and etc. this work study on a polygeneration system based on solar and biomass to produce power, heating, hot water and hydrogen. Solar radiations can be collected by parabolic trough collectors (PTC) which are using as a solar thermal system in many power plants in the world because of their high efficiency and low cost [1]. Recently, several scholars have been studied on polygeneration energy system performance. Maraver et al. [2] presented a multigeneration energy system driven by biomass for producing power, heating, cooling and fresh water. They analyzed the proposed system from the thermodynamic point of view. Also, they examined the system operation by changing working fluids of ORC subsystem. Noorpoor et al. [3]suggested a multi-generation energy system based on solar and biomass for producing power, heating, cooling and fresh water. They promoted thermodynamic performance of the system by system multiobjective optimization. Bicer and Dincer [4] proposed a multi-generation energy system with power, heating, cooling, and hydrogen as outputs. Moreover, energy and exergy efficiencies of this solar and geothermal-based system are 10.8 and 46.3%. Taheri et al. [5]proposed a multigeneration system includes power, cooling, and hydrogen production with biomass and LNG regasification cycle as energy sources. They found that combustion subsystem has largest exergy destruction, also they studied on thermodynamic performance improvement by system optimization. Boyaghchi et al. [6] applied the thermodynamic analysis of a multigeneration system based on geothermal and liquefied natural gas for producing power, heating, cooling, and hydrogen. As a result of their study,overallexergy efficiency and the amount of generated hydrogen were calculated to be 38% and 1.4 g/s, respectively. Calise et al. [7] suggested a multigeneration energy system based on the renewable energy source. Power, heating, cooling and hot water produced as useful outputs of the system driven by solar energy. They found that required solar field area varies from 250-300 m^2. Moreover, they investigated effects of key parameters on the thermodynamic performance of the system through sensitivity analysis. Akrami et al. [8] calculated energy and exergy efficiencies of a multi-generation energy system based on geothermal energy. Outputs of their system are power, heating, cooling and hydrogen. They showed that most exergy destruction occurs in organic Rankine cycle (ORC) turbine. Islam and Dincer [9] examined the thermodynamic performance of a multi-generation energy system driven by solar and geothermal for producing power, space heating, cooling, and drying system. They enumerated advantages of using multi renewable sources over single energy source. Sahoo et al. [10] represented a polygeneration energy system for producing power, heating, cooling, fresh water based on solar and biomass energy. As a result of their study, the required surface for PTC collector was about 31000 m^2 and generated electricity in this system was about 4887 KW.

In this paper a polygeneration system based on solar and biomass is proposed for khouzestan province in Iran. Since this region has sufficient solar radiation and biomass production [11]. Bagasse is designated as biomass fuel. Solar radiations are collected through PTC collector. In biomass burner, exec air and bagasse are combined and burned to provide other portion of system required energy. Useful outputs of the system are power, heating, hot water and hydrogen. Power generated by steam Rankine cycle (SRC) turbine, heating is produced by SRC heat exchanger, hydrogen produced by proton exchange membrane (PEM) electrolyzer and hot water produced by domestic water heater. Energy and exergy efficiencies and exergy destruction rate of each element are calculated to assess the performance of the system. Moreover, sensitively analysis is carried out to show the effect of key parameters on polygeneration system operation.

2. System Description

Fig 1. represents schematic of the proposed cogeneration system. Solar energy and biomass supply the required input energy for system and power, hot water, heating and hydrogen are useful outputs of the system. Suggested cogeneration system has four subsystems are called PTC subsystem, biomass combustion subsystem, SRC subsystem and PEM subsystem. In PTC subsystem, solar radiation can be collected by PTC. Therminol VP-1 selected as a stable and suitable working fluid for solar collector in high temperature. Baggase is a type of sugar cane which is a by-product in sugar industries. Baggase is selected as biomass fuel and combusted in biomass burner. Hot exhaust gasses of bagasse combustion enter to heat exchanger to prepare required heating load to warm domestic hot water. In SRC subsystem, hot combustion gases pass through a steam turbine to produce power. Heating power is produced by heat exchanger1. A portion of produced power is used by PEM electrolyzer to produce hydrogen. In PEM subsystem, water separates to hydrogen and oxygen by electrolysis reaction through cathode and anode in PEM electrolyzer. 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 is attained from nine large sugar production factories [12].

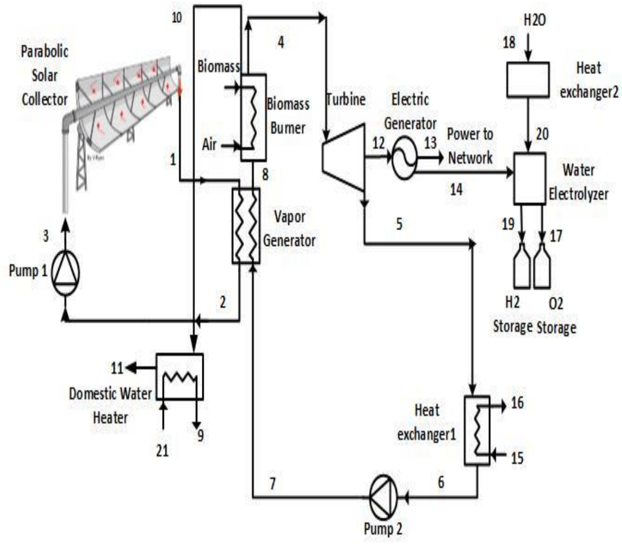

Fig1. Schematic of suggested cogeneration cycle

1. Thermodynamic analysis

In this section, the energy and exergy analysis are carried out by using the following assumptions:

- The reference-environment temperature and pressure are T_0 = 298 K, P_0 = 100 KPa.
- The changes in kinetic, and potential energy and exergy terms are negligible.
- HHV for bagasse is 17000 kJ/kg.
- The higher heating value (HHV) is the primary contributor to the chemical exergy
-
- of a biomass fuel and obtained from the below equation [13]:

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

Exergy destruction rates and exergy efficiencies for components of the multigeneration system based on the below exergy balance is listed in Table 1.
Energy and exergy efficiencies based on first and second lows of thermodynamic for the quadruple generation system are stated as follows:

$$\eta_{multi} = \frac{\dot{W}_{direct-use} + \dot{E}_{DWH} + \dot{E}_{heating} + \dot{m}_{19} HHV_{H_2}}{\dot{E}_{BC} + \dot{E}_s} \quad (1)$$

$$\varepsilon_{multi} = \frac{\dot{W}_{direct-use} + \dot{E}x_{DWH} + \dot{E}x_{heating} + \dot{m}_{19} ex_{H_2}^{ch}}{\dot{m}_{bio} ex_{bio}^{ch} + \dot{E}x_s} \quad (2)$$

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

.

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

Components	Exergy Destruction Rate	Exergy Efficiency
PTC	$E\dot{x}_{D,PTC} = E\dot{x}_s - \dot{m}_1(ex_1 - ex_3)$	$1 - \frac{E\dot{x}_{D,PTC}}{E\dot{x}_s}$
Heat Exchanger1	$E\dot{x}_{D,HX1} = \dot{m}_5(ex_5 - ex_6) - \dot{m}_{15}(ex_{16} - ex_{15})$	$1 - \frac{E\dot{x}_{D,HX1}}{\dot{m}_5(ex_5 - ex_6)}$
Turbine	$E\dot{x}_{D,turb} = \dot{m}_4(ex_4 - ex_5) - \dot{W}_{turb}$	$1 - \frac{E\dot{x}_{D,turb}}{\dot{m}_4(ex_4 - ex_5)}$
Electrolyzer	$E\dot{x}_{D,PEM} = ex_{14} + \dot{m}_{18}(ex_{20} - ex_{18}) - (ex_{19} + ex_{17})$	$1 - \frac{E\dot{x}_{D,PEM}}{ex_{14} + \dot{m}_{18}(ex_{20} - ex_{18})}$

Biomass combustor	$\dot{Ex}_{D,BC} = \dot{Ex}_{bio} + \dot{m}_{air}ex_{air} - \dot{m}_{10}ex_{10} - \dot{m}_4(ex_4 - ex_8)$	$1-\frac{\dot{Ex}_{D,BC}}{\dot{Ex}_{bio} + \dot{m}_{air}ex_{air} - \dot{m}_{10}ex_{10}}$

1. Result and discussion

The suggested multi generation system based on solar energy and energy of bagasse combustion as energy sources to provide electricity, heating power, hydrogen and hot water. The studied system is proposed for coastal area of the southern region of Iran. The average solar daily radiation on a horizontal surface is extracted from NASA [14]and is converted to instantaneous solar radiation. The calculations are conducted by formulating first and second laws of thermodynamics and solving the equations by using EES (Engineering Equation Solver) software[15]. In Table 2 input data and values for thermodynamic modeling of the proposed system value are listed.

Table 2. Input data for thermodynamic modeling

Parameter	**Value**
Turbine inlet temperature (^{0}C)	515
Turbine inlet pressure (kPa)	6000
Turbine pressure ratio	45
Heat exchanger1 temperature difference (^{0}C)	10
Turbine isentropic efficiency	0.85
Pumps isentropic efficiency	0.7
Hydrogen High Heating Value (MJ/kg)	141.88

Table 3 summarizes the performance specifications of the multi generation.

Table 3. Thermodynamic performance of the multi generation system

Parameter	**Value**
Total electricity output (kW)	37.01
Direct use electricity (kW)	20.34
Electricity to electrolyzer (kW)	16.67
Heating power (kW)	122.2
Hydrogen production (kg/h)	0.288
Hot water production (kg/h)	18
Aperture area of solar collector (m^2)	109.8
Mass flow rate of bagasse (kg/h)	32.4
Thermal efficiency (%)	58.24
Exergy efficiency (%)	51.68

Figure 2 shows Exergy destruction of each component of the multi generation system. Biomass combustor, parabolic trough solar collector and proton exchange membrane electrolyzer are major sources of inefficiencies. In biomass combustor, the combustion of bagasse occurs and chemical reactions are the main sources of inefficiencies. In parabolic trough solar collector, the temperature difference between the receivers and the heat transfer fluid is the reason of high exergy destruction rates. In PEM electrolyzer, electrolysis reactions are resulted to high amount of exergy destruction rate. These three components have main potential for system performance improvement.

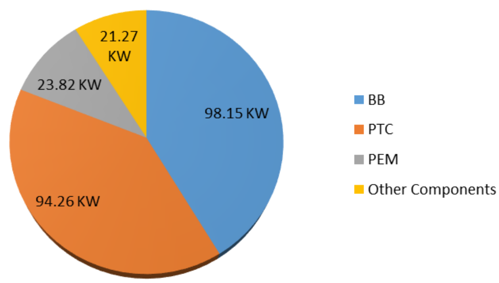

Figure 2. Exergy destruction rates of the components

As shown in figure 3 and 4 shows thermodynamic performance of the system useful outputs are comprised in four different cases such as single generation (SG) case, combined heat and power (CHP) case, combined heat and power with hydrogen production (CCHP+PEM) case, quadruple generation including hot water, power, heating and hydrogen. In all cases, the amounts of energy and exergy inputs are the same in order to make an accurate comparison. As it is obvious in figure 3, by adding one more product to the single generation system, the energy efficiency improves. Since, 45% of electrical power is fed to PEM for hydrogen production and a fraction of its losses in the process of hydrogen production, by adding PEM to CHP case, the energy efficiency drops down due to losses of PEM. As it is seen in the case of a quadruple(DWH-PEM) system, the energy efficiency is lower than (CHP) case. The reason is obviously the same for (CHP+PEM) as well.

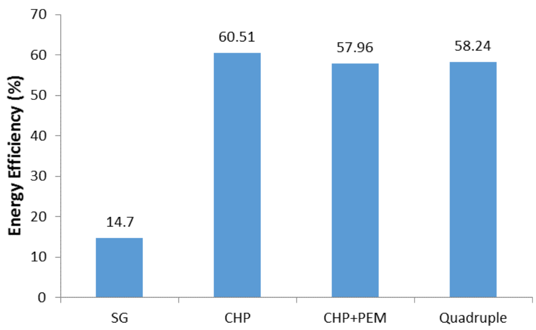

Figure 3. Advantages of cogeneration system in terms of energy efficiency

Similarly, in figure 4, by combining a heat exchanger to a single generation cycle in order to generate heating power, the exergy efficiency grows up. By integrating PEM to a CHP system, 45% of electric power generated by the system is consumed by electrolyzer and a portion of it is wasted during the process of electrolyzing the water. Hence, the exergy efficiency is lower than the CHP case. Quadruple (CHP+DWH+PEM)) case is less efficient than CHP case.

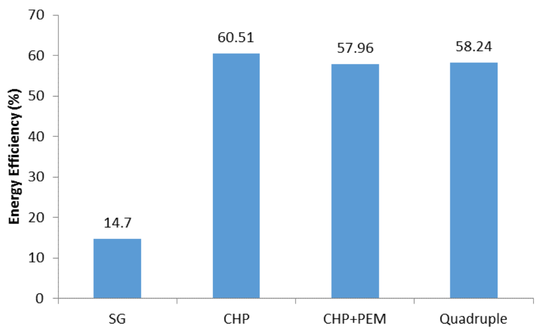

Figure 4. Advantages of cogeneration system in terms of exergy efficiency

6. Sensitivity Analysis

6.1. Effect of turbine inlet pressure on the thermal and exergy efficiencies of the quadruple generation system

Figure 5 illustrates the effect of turbine inlet pressure on thermal and exergy efficiencies of the overall system. By increasing turbine inlet pressure from 5600 KPa to 6400 KPa, the thermal efficiency of the system improves because the useful energy output of the system increases. By this variation of turbine inlet pressure, exergy efficiency of the multigeneration system improves due to the increment of the useful exergy output of the system.

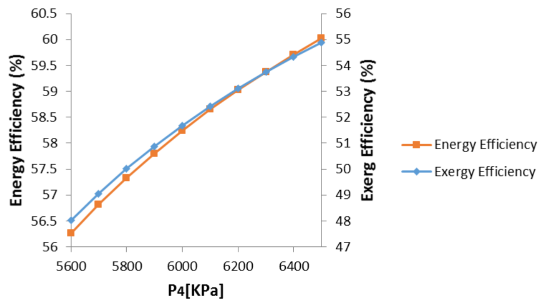

Figure 5. Effect of turbine inlet pressure on thermal and exergy efficiencies of the quadruple generation system

6.2. Effect of average daily Insolation on iorizontal Surface on the thermal and exergy efficiencies of the multi generation system

Figure 6 presents the effect of average daily insolation on horizontal surface on thermal and exergy efficiencies of the quadruple generation system. By increasing the average daily insolation on horizontal surface from 8.2 to 8.6, the thermal efficiency of the system drops down due to increasing in solar radiations and exergy efficiency stays constant.

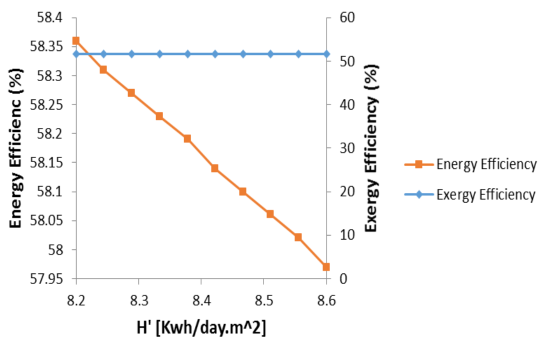

Figure 6. Effect of average daily insolation on horizontal surface on thermal and exergy efficiencies of the quadruplegeneration system

6.3. Effect of temperature difference of vapor generator on the thermal and exergy efficiency of the multi generation system

The influence of temperature difference of vapor generator on thermal and exergy efficiencies of the quaruple generation system is presented in figure 7. It is obvious that by increasing the temperature difference of vapor generator from 5 to 20, both thermal and exergy efficiencies improve. Higher temperature difference requires higher mass flow rate of Rankine cycle and as a result the amount of energy and exergy feeding to turbine increases.

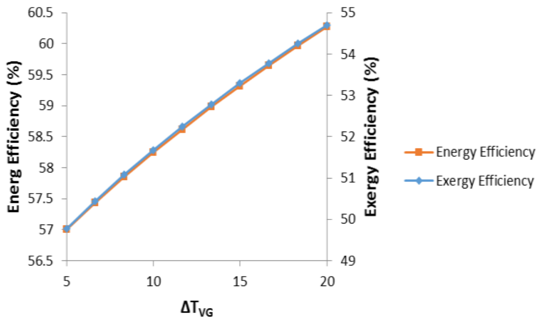

Figure 7. Effect of temperature difference of evaporator1 on thermal and exergy efficiencies of the quadruple generation system

2. Conclusion

In this article, a novel quadruple-generation energy system with solar and biomass as energy inputs to generate useful outputs such as electricity, heating power, hot water and hydrogen is suggested for the coastal area of the southern region of Iran. The sensitivity analysis is carried out in order to see the influence of design parameters of the system on overall energy and exergy efficiencies. Therefore, concluding remarks are extracted from the results of the thermodynamic study:

- The thermal and exergy efficiencies of the quadruple-generation system are found to be 58.24% and 51.68% in the case of that collector aperture area and the biomass mass flow rate is calculated to be 109.8m^2 and 32.4kg/s.
- The results of exergy analysis indicate that biomass combustor, parabolic trough solar collector and proton exchange membrane electrolyzer are the most inefficient components in comparison to others.

Nomenclature	
ex	Specific exergy (KJ/kg)
m·	Mass flow rate (Kg/s)
T	Temperature (°C)
BC	Biomass Combustor
bio	biomass
ch	chemical
d	Destruction
p	pressure
HHV	High heating value
Multi	Multi generation system

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