



Available online at www.sciencedirect.com





Solar Energy 112 (2015) 290-299

www.elsevier.com/locate/solener

Energy and exergy analyses of a solar-biomass integrated cycle for multigeneration

Farrukh Khalid^{*}, Ibrahim Dincer¹, Marc A. Rosen

Faculty of Engineering and Applied Science, University of Ontario Institute of Technology, 2000 Simcoe Street North, Oshawa, Ontario L1H 7K4, Canada Received 24 July 2014; received in revised form 21 November 2014; accepted 24 November 2014

Communicated by: Associate Editor Michael Epstein

Abstract

A biomass and solar integrated system for multigeneration of useful outputs, in which two renewable energy sources are combined to produce multiple outputs (e.g., power, cooling, hot water, heated air), is developed and presented. Energy and exergy analyses are used to assess the performance of the cycle, and the effects of various system parameters on energy and exergy efficiencies of the overall system and its subsystems are examined. The overall energy and exergy efficiencies of the system are found to be 66.5% and 39.7% respectively. Furthermore, the effect is also investigated of reference-environment temperature on energy and exergy efficiencies for the system, when operated only on biomass and solar energy.

© 2014 Elsevier Ltd. All rights reserved.

Keywords: Biomass; Efficiency; Exergy; Multigeneration; Solar energy

1. Introduction

Energy usually plays a vital role in the development of a nation. With the gradual depletion of conveniently available fossil fuel reserves, people are seeking other energy sources which are long lasting as well as environmentally benign, like renewable energy. The main renewable energy sources in use nowadays are solar, geothermal, wind, biomass and hydro (Ahmadi et al., 2013). Biomass is mainly derived from living or dead matter present on earth (Cohce et al., 2011). Solar energy can be collected in various ways, e.g., concentrated solar panel and heliostat. In this study, a heliostat field and central receiver are used.

* Corresponding author.

Energy challenges can, to some extent, be overcome by using energy resources more efficiently, and sometimes this can be achieved via trigeneration and multigeneration (Chicco and Mancarella, 2008). Another way of efficiently using energy resources is to integrate them in such a manner that the deficiencies of one energy source are overcome by the other, often leading to the better utilisation of the energy resources.

A number of studies have been reported on trigeneration and multigeneration. Using energy and exergy analyses on a waste heat recovery-based trigeneration system, Khaliq et al. (2009) examined the effect of exhaust inlet gas temperature on the energy and exergy efficiencies and found that energy efficiency increases with increasing exhaust inlet gas temperature while exergy efficiency decreases. Malico et al. (2009) developed a trigeneration system to meet the demands of a hospital for electricity, heating, cooling and hot water, and performed an economic feasibility analysis. An exergy analysis of a Gas

E-mail addresses: farrukh.khalid@uoit.ca (F. Khalid), ibrahim. dincer@uoit.ca (I. Dincer), marc.rosen@uoit.ca (M.A. Rosen).

¹ Department of Mechanical Engineering, KFUPM, Dhahran 31261, Saudi Arabia.

Nomenclature

С	compressor	Subscri	pts
Ėx	exergy rate (kW)	a	absorber
ex	specific exergy (kJ/kg)	bio	biomass
GT	Gas turbine	c	compressor
h	specific enthalpy (kJ/kg)	ch	chemical
HE	heat exchanger	co	condenser
k	specific heat ratio	cr	central receiver
LHV	lower heating value (kJ/kg)	d	destruction
'n	mass flow rate (kg/s)	e	evaporator
Р	pressure (kPa)	g	generator
RT	Rankine turbine	gtc	Gas Turbine Cycle
Ż	heat rate (kW)	ha	hot Air
S	specific entropy (kJ/kg-K)	hw	hot water
Т	temperature (K)	is	isentropic
v	specific volume (m ³ /kg)	ov	overall
Ŵ	work rate (kW)	р	pump
		ph	physical
Greek letters		rc	Rankine Cycle
η	energy efficiency	S	source
ψ	exergy efficiency	sol	solar
Φ	exergy to energy ratio of the fuel	t	turbine
λ	stoichiometric constant in biomass combustion reaction in Eq. (1) (moles)	<i>x</i> , <i>y</i> , <i>z</i>	number of atoms of carbon, hydrogen and oxy- gen in biomass (atoms/molecule)
α , β , δ , γ number of atoms of carbon, hydrogen, nitro-		0	ambient (or reference environment) condition
	gen and oxygen in biomass (atoms/molecule)	1, 2,	. 44 state numbers

Turbine for trigeneration by Khaliq (2009) determined that the maximum exergy destruction occurs in the combustion chamber and the steam generator. Al-Sulaiman et al. (2012) performed energy and exergy analyses of a biomass trigeneration system using an organic Rankine Cycle, and found that the maximum exergy efficiency of the organic Rankine Cycle increases from 13% to 28% when they switch from single generation to trigeneration. Ozturk and Dincer (2013) studied a solar-based multigeneration system and found its exergy efficiency to be about 57%. An analysis by Dincer and Zamfirescu (2012) of renewable energy-based multigeneration systems demonstrated that the exergy efficiencies vary from 55% to 65%, depending upon the degree of cogeneration used. Ozturk and Dincer (2013) showed that, through the integration of various systems, multigeneration increases energy and exergy efficiencies. Dincer and Zamfirescu (2011) determined that renewable energy-based multigeneration reduces fuel prices and harmful pollutant emissions, compared to conventional systems. The above studies indicate that multigeneration via the integration of two renewable energy sources can be beneficial.

The specific objectives of this paper are to propose and to assess with energy and exergy analyses a new integrated multigeneration system using biomass and solar energy, including the determination of overall energy and exergy efficiencies of the multigeneration system and its subsystems; and to carry out a parametric study to determine the effects of various parameters on the overall energy and exergy efficiencies of the multigeneration system and its subsystems.

2. System description

The proposed multigeneration system (see Fig. 1) uses two renewable energy sources: solar and biomass. It contains two Rankine and two Gas Turbine Cycles, as well as a absorption cooling cycle. The main outputs of the proposed system are electric power, cooling, hot water and hot air. The most significant part of this system is concentrated solar collector. The solar energy from the sun is collected through a heliostat tower. The heliostat tower reflects the incident solar energy to the central receiver where it absorbs the heat and transfers this heat to the heat transfer fluid. In the concentrated solar collector, the two important aspects for the performance are heliostat aperture area and direct normal irradiation.

2.1. Gas Turbine Cycle 1

Fresh air enters Compressor 1 and the resulting compressed air enters the combustion chamber where it mixes



Fig. 1. Schematic diagram of the biomass and solar energy integrated cycle for multigeneration.

with biomass and burns to produce high-temperature combustion gases. These highly pressurized gases pass through the Gas Turbine 1 to produce power. The exhaust gases from Gas Turbine 1 are then divided into two streams.

2.2. Gas Turbine Cycle 2

Compressed air from the compressor of Gas Turbine Cycle 2 flows through Heat Exchanger 1 where the compressed air is heated by a portion of exhaust gases from Gas Turbine 1. The heated compressed air is then expanded in the Gas Turbine 2 to produce electrical power and then goes to Heat Exchanger 2 where it transfers heat and then goes to the compressor where it is compressed.

2.3. Rankine Cycle 1

Pressurized water from Pump 1 of Rankine Cycle 1 is heated in Heat Exchanger 2 using both the exhaust air from the Gas Turbine 2 and exhaust gases from Heat Exchanger 1. The resulting steam expands in Rankine Turbine 1 to produce the work while the exhaust steam passes through Condenser 1. The condensate is then pressurized with a pump. The waste heat from the condenser is utilised to heat the water, which is one product output.

2.4. Rankine Cycle 2

Solar radiation from the sun is incident on the heliostats, which are focused on the central receiver and heat oil (Dowtherm-A) to a high temperature. In Heat Exchanger 4 heat from the heated oil is transferred to the pressurized water from Pump 2. The water is superheated using a portion of the exhaust gases from Gas Turbine 1. The superheated steam expands in a steam turbine producing work, while the exhaust steam is condensed in the condenser and then pressurized in Pump 2.

2.5. Absorption cooling cycle

Heat is transferred from the oil exiting Heat Exchanger 4 to the generator of the absorption cooling cycle and the oil then returns to the central receiver. After receiving the heat, a portion of the water in the generator is evaporated and enters the condenser. There, the water vapor is cooled using a cooling source, converting it back to water, and throttled in an expansion valve. The water temperature drops as it enters the evaporator. After absorbing the cooling load in evaporator, the water is vaporized and enters the absorber, where it mixes with the lean mixture of LiBr–H₂O, which comes from the generator through a heat exchanger and expansion valve, and is converted to a rich mixture of LiBr–H₂O. Then the mixture from the absorber is pumped to the generator through a Heat Exchanger 6.

3. Thermodynamic analysis

Energy and exergy analyses are performed for the proposed multigeneration system, in order to provide the information about its performance, efficiency and emissions.

The following assumptions are made for the analysis of the integrated system:

- 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.
- The turbines and pumps are adiabatic.
- The isentropic efficiencies of turbines and pumps are 85% (Srinivas et al., 2007).
- There are no heat losses from the heat exchangers.
- The pressure losses in all heat exchangers and pipelines are negligible.
- Air is treated as an ideal gas.
- The exhaust gases exiting the Gas Turbine 1 are treated like air.

As shown in Fig. 1, biomass enters the combustion chamber at point 4 and air enters at point 3. The composition of biomass in this study is given in Table 1.

The biomass is combusted according to the following reaction:

$$C_x H_y O_z + \lambda (O_2 + 3.76 N_2) \rightarrow a CO_2 + b H_2 O + c N_2$$
 (1)

The LHV_{dry} of biomass in kJ/kg can be determined as (Ahmadi et al., 2013):

$$LHV_{dry} = \frac{400,000 + 100,600y - \frac{z}{1+0.5y}(117,600 + 100,600y)}{12 + y + 16z}$$
(2)

The chemical exergy of fuel (ex_f) is determined using the exergy-to-energy ratio (Φ) provided by Szargut et al. (1988):

$$\Phi = \frac{ex_f}{LHV_{dry}} \tag{3}$$

The exergy-to-energy ratio for a fuel $(C_{\alpha}H_{\beta}N_{\delta}O)$ is expressed by Szargut et al. (1988) as:

$$\Phi = 1.0401 + 0.1728 \frac{\beta}{\alpha} + 0.0432 \frac{\delta}{\alpha} + 0.2169 \frac{\Upsilon}{\delta} \left(1 - 0.2062 \frac{\beta}{\alpha} \right)$$
(4)

Table 1 Input data of biomass.

Quantity	Value			
Biomass type	Dry Olive pits			
Elemental analysis (dry basis by weight)				
Carbon (C)	48.81%			
Hydrogen (H)	6.23%			
Oxygen (O)	43.48%			
Nitrogen (N)	0.36%			
Sulfur (S)	0.02%			
Air fuel ratio	5.75			
Adiabatic flame temperature	2561 K			
G G (1 (2001)				

Source: Sami et al. (2001).

The specific chemical and physical exergies of the gases from the combustion chamber are expressible as follows (Dincer and Rosen, 2013):

$$\operatorname{ex}_{\operatorname{ch5}} = \sum x_k \operatorname{ex}_{\operatorname{ch}}^k + RT_0 \sum x_k \ln x_k \tag{5}$$

and

$$ex_{ph5} = h_5 - h_0 - T_0(s_5 - s_0)$$
(6)

The outlet temperature (T_3) of Compressor 1 can be calculated as follows:

$$T_3 = T_2 \left(\frac{P_3}{P_2}\right)^{\frac{k-1}{k\eta_c}} \tag{7}$$

where k is the specific heat ratio and η_c is the compressor isentropic efficiency.

The outlet temperature (T_7) of Gas Turbine 1 can be determined using:

$$\frac{T_6}{T_7} = \left(\frac{P_6}{P_7}\right)^{\frac{\eta_1(k-1)}{k}} \tag{8}$$

where η_t is the turbine isentropic efficiency.

The exergy destruction rate can be calculated for Gas Turbine 1 using

$$\dot{m}_6 \operatorname{ex}_6 = \dot{m}_7 \operatorname{ex}_7 + \dot{W}_{\text{gtc1}} + \dot{\mathrm{Ex}}_{\text{dgtc1}} \tag{9}$$

for Rankine Turbine 1 using

$$\dot{m}_{26} ex_{26} = \dot{m}_{27} ex_{27} + W_{t1} + Ex_{dt1}$$
(10)

for Condenser 1 using

$$\dot{m}_{27} \mathbf{e} \mathbf{x}_{27} + \dot{m}_{11} \mathbf{e} \mathbf{x}_{11} = \dot{m}_{28} \mathbf{e} \mathbf{x}_{28} + \dot{Q}_{col} \left(1 - \frac{T_0}{T_s} \right) \\ + \dot{\mathbf{E}} \mathbf{x}_{dc1} + \dot{m}_{12} \mathbf{e} \mathbf{x}_{12}$$
(11)

for the evaporator using

$$\dot{m}_{37} \mathrm{ex}_{37} + \dot{Q}_{\mathrm{e}} \left(\frac{T_{\mathrm{e}}}{T_0} - 1 \right) = \dot{m}_{38} \mathrm{ex}_{38} + \dot{\mathrm{E}} \mathrm{x}_{\mathrm{de}}$$
 (12)

and for the absorber using

$$\dot{m}_{44} \mathbf{ex}_{44} + \dot{m}_{38} \mathbf{ex}_{38} = \dot{m}_{39} \mathbf{ex}_{39} + \dot{Q}_{a} \left(1 - \frac{T_{0}}{T_{s}} \right) + \dot{E} \mathbf{x}_{da}$$
(13)

3.1. Energy efficiencies

.

.

The energy efficiency is defined as the ratio of useful energy output to the total energy input (Ozturk and Dincer, 2013). Here, energy efficiency measures are determined for eight systems in the overall multigeneration system. For Rankine Cycle 1, Rankine Cycle 2, Gas Turbine Cycle 1 and Gas Turbine Cycle 2, respectively, we can write the following energy efficiencies:

$$\eta_{\text{gtcl}} = \frac{W_{\text{gtcl}} - W_{\text{cl}}}{\dot{m}_4 \text{LHV}_{\text{dry}}} \tag{14}$$

$$\eta_{\rm rc1} = \frac{\dot{W}_{\rm t1} - \dot{W}_{\rm p1}}{(\dot{m}_{32}h_{32} + \dot{m}_{13}h_{13}) - (\dot{m}_{14}h_{14} + \dot{m}_{29}h_{29})}$$
(15)

$$\eta_{\rm rc2} = \frac{W_{\rm t2} - W_{\rm p2}}{(\dot{m}_{17}h_{17} + \dot{m}_9h_9) - (\dot{m}_{18}h_{18} + \dot{m}_{10}h_{10})} \tag{16}$$

$$\eta_{\text{gtc2}} = \frac{\dot{W}_{\text{gtc2}} - \dot{W}_{\text{c2}}}{(\dot{m}_8 h_8 - \dot{m}_{13} h_{13})} \tag{17}$$

For the absorption cooling cycle, the cooling performance is expressed by the coefficient of performance (not by conventional efficiency since the values may become greater than 100%) which is defined as the ratio of cooling load obtained from the evaporator to the total heating load input to the generator. Here, the COP is defined for the absorption cooling system considered as (Ozturk and Dincer, 2013):

$$COP = \frac{\dot{Q}_{e}}{\dot{m}_{18}h_{18} - \dot{m}_{19}h_{19}}$$
(18)

For the hot air heater, hot water heater and the overall multigeneration system, respectively, we can write the following energy efficiencies:

$$\eta_{\rm ha} = \frac{\dot{m}_{34}h_{34} - \dot{m}_{33}h_{33}}{\dot{m}_{14}h_{14} - \dot{m}_{15}h_{15}} \tag{19}$$

$$\eta_{\rm hw} = \frac{\dot{m}_{12}h_{12} - \dot{m}_{11}h_{11}}{\dot{m}_{27}h_{27} - \dot{m}_{28}h_{28}} \tag{20}$$

$$\eta_{\rm ov} = \frac{(\dot{W}_{\rm gtc1} + \dot{W}_{\rm t1} + \dot{W}_{\rm gtc2} + \dot{Q}_{\rm e} + \dot{W}_{\rm t2} + \dot{m}_{\rm 34}h_{\rm 34} + \dot{m}_{\rm 12}h_{\rm 12}) - (\dot{W}_{\rm in} + \dot{m}_{\rm 33}h_{\rm 33} + \dot{m}_{\rm 11}h_{\rm 11})}{\dot{m}_{\rm 4}{\rm LHV} + \dot{Q}_{\rm Solar}}$$
(21)

where
$$\dot{W}_{in} = \dot{W}_{c1} + \dot{W}_{c2} + \dot{W}_{p1} + \dot{W}_{p2}$$
.

3.2. Exergy efficiencies

The exergy efficiency of a process is defined as the ratio of useful exergy output to the total exergy input (Ozturk and Dincer, 2013). Here, exergy efficiency measures, corresponding to those for which energy efficiency measures were written in the last subsection, are written:

$$\psi_{\text{gtcl}} = \frac{W_{\text{gtcl}} - W_{\text{cl}}}{\dot{m}_4 \text{ex}_{\text{f}}} \tag{22}$$

$$\psi_{\rm rc1} = \frac{W_{\rm t1} - W_{\rm p1}}{(\dot{m}_{32} e x_{32} + \dot{m}_{13} e x_{13}) - (\dot{m}_{14} e x_{14} + \dot{m}_{29} e x_{29})}$$
(23)

$$\psi_{\rm rc2} = \frac{W_{\rm t2} - W_{\rm p2}}{(\dot{m}_{\rm 17} e {\bf x}_{\rm 17} + \dot{m}_{\rm 9} e {\bf x}_{\rm 9}) - (\dot{m}_{\rm 18} e {\bf x}_{\rm 18} + \dot{m}_{\rm 10} e {\bf x}_{\rm 10})}$$
(24)

$$\psi_{\text{gtc2}} = \frac{W_{\text{gtc2}} - W_{\text{c2}}}{(\dot{m}_8 \text{ex}_8 - \dot{m}_{13} \text{ex}_{13})}$$
(25)

$$\operatorname{COP}_{\mathrm{ex}} = \frac{\dot{Q}_{\mathrm{e}} \left(\frac{T_{0}}{T_{e}} - 1 \right)}{\dot{Q}_{\mathrm{d}} \left(1 - \frac{T_{0}}{T_{\mathrm{s}}} \right)}$$
(26)

$$\psi_{\rm ha} = \frac{\dot{m}_{34} {\rm ex}_{34} - \dot{m}_{33} {\rm ex}_{33}}{\dot{m}_{14} {\rm ex}_{14} - \dot{m}_{15} {\rm ex}_{15}} \tag{27}$$

$$\psi_{\rm hw} = \frac{\dot{m}_{12} \mathbf{e} \mathbf{x}_{12} - \dot{m}_{11} \mathbf{e} \mathbf{x}_{11}}{\dot{m}_{27} \mathbf{e} \mathbf{x}_{27} - \dot{m}_{28} \mathbf{e} \mathbf{x}_{28}}$$

$$\psi_{\rm ov} = \frac{\left(\dot{W}_{\rm gtcl} + \dot{W}_{\rm tl} + \dot{W}_{\rm gtc2} + \dot{Q}_{\rm c} \left(\frac{T_{\rm s}}{T_{\rm o}} - 1\right) + \dot{W}_{12} + \dot{m}_{34} \mathbf{e} \mathbf{x}_{34} + \dot{m}_{12} \mathbf{e} \mathbf{x}_{12}\right) - \left(\dot{W}_{\rm in} + \dot{m}_{33} \mathbf{e} \mathbf{x}_{33} + \dot{m}_{11} \mathbf{e} \mathbf{x}_{11}\right)}{\dot{m}_{4} \mathbf{e} \mathbf{x}_{\rm f} + \dot{\mathbf{E}} \mathbf{x}_{\rm sol}}$$

$$(28)$$

where $\dot{Q}_{d} = \dot{m}_{18}h_{18} - \dot{m}_{19}h_{19}$ is the heat input rate to the generator of the absorption cooling cycle.

4. Results and discussion

In performing the energy and exergy analyses of the solar biomass integrated multigeneration system, values of mass flow rate (kg/s), temperature (K), pressure (kPa), specific enthalpy (kJ/kg) and specific exergy (kJ/kg) are determined for the each state of the system (Table 2). The reference-environment conditions are taken to be the ambient conditions, for which the temperature and pressure are 298 K and 100 kPa, respectively. Thermodynamic values are calculated using Engineering Equation Solver (EES) software which is a widely used software package. It can generally be used to solve n non-linear equations for n unknowns. It can simplify problems including thermodynamic cycles and easily minimize the chances of calculation errors when such cycles solve manually. However, the code generated to solve problems can be very sensitive to initial guesses, and will sometimes not meet to a solution even though the entered equations are correct.

The values of all outputs and inputs of various components of the multigeneration system are tabulated in Table 3. The maximum exergy destruction rate to occur in the combustion chamber is shown in Fig. 2. This is associated with the fact that a large amount of entropy is generated due to combustion and large heat transfers across large temperature differences, resulting in a large exergy destruction. Efforts thus appear to be merited to reduce the exergy destruction in the combustion chamber and its fuel use, provided it can be done cost-effectively. The next highest exergy destruction is in Gas Turbine 1. The third highest exergy destruction rate takes place in Heat Exchanger 3.

The overall energy and exergy efficiencies of the multigeneration system are found to be 66.5% and 39.7% respectively. The energetic and exergetic COPs of the single effect absorption cycle are found to be 0.76 and 0.14 respectively. The exergetic COP is lower than the energetic COP because there are considerable losses in the absorption system, which are accounted for with exergy analysis but are not in the energy analysis. In addition, the energy and exergy efficiencies respectively are found to be 42.1% and 31.6%for Gas Turbine Cycle 1, 29.3% and 48.4% for Rankine Cycle 1, 7.7% and 17.8% for Rankine Cycle 2, and 30.8%and 39.8% for Gas Turbine Cycle 2.

4.1. Effect of ambient temperature

Ambient temperature affects the performance of most thermodynamic systems. For instance, variations in

 Table 2

 Input and calculated process data for the multigeneration system.

0Water100 $-$ 298104.80Air100 $-$ 298298.41 $-$ 100 $-$ 4500 $-$ 2Air10040298298.4	0 0 0 187.5 24,747 526 1
0 Air 100 - 298 298.4 1 - 100 - 4500 - 2 Air 100 40 298 298.4	0 0 187.5 24,747 526 1
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	- 0 187.5 24,747 526 1
2 Air 100 40 298 298.4	0 187.5 24,747 526.1
	187.5 24,747 526 1
3 Air 500 40 502.7 506.1	24,747 526 1
4 Biomass 100 4.2 298 18,588	526.1
5 Combustion gases 500 44.2 1600 2335	520.1
6 Combustion gases 500 44.2 1600 2335	526.1
7 Exhaust gases 100 44.2 999.4 1325	-4.323
8 Exhaust gases 100 30.94 999.4 1325	-4.323
9 Exhaust gases 100 13.26 999.4 1325	-4.323
10 Flue gases 100 13.26 301.4 385.7	-391.9
11 Water 100 35 298 104.2	0
12 Water 100 35 353 334.3	18.94
13 Exhaust gases 100 30.94 860.9 1142	-129
14 Exhaust gases 100 30.94 556.6 738.1	-360.2
15 Flue gases 100 30.94 402.1 542.9	-469.8
16 Oil 100 10 363 125.3	10.31
17 Oil 100 10 493 379.2	86.8
18 Oil 100 10 393 179.8	22.01
19 Oil 100 10 363 125.3	10.31
20 Water 4000 5 349.5 322.7	20.58
21 Water 4000 5 443.3 721.5	118.4
22 Water 4000 5 673 3213	1201
23 Water 40 5 349 2404	321.4
24 Water 40 5 349 317.6	16.37
25 Water 8000 6 367.7 402	37.38
26 Water 8000 6 673 3138	1246
27 Water 80 6 366.7 2324	390.7
28 Water 80 6 366.7 391.7	28.78
29 Air 100 10 300 300.4	0.006713
30 Air 800 10 586.4 593	267
31 Air 800 10 1100 1161	629
32 Air 100 10 681.2 695.4	142.3
33 Air 100 100 298 298.4	0
34 Air 100 100 358 358.8 25 Nu 7.4 0.1770 254.51 2672	5.336
35 Water /.4 0.1/18 354.51 2652	2344
36 Water /.4 0.1/18 313.05 167.7	57.71
3/ Water .68 0.1/78 2/4.4/5 16/./	56.69
38 Water .68 $0.1//8$ 2/4.4/5 2503	2180
39 Water/LiBr .68 3 310 105.9	30.63
40 Water/LiBr 7.4 3 312.07 107.9	34.36
41 Water/LiBr 7,4 3 357,39 196,9	116.7
42 Water/LiBr /.4 2.822 363 223.2	142.9
45 Water/LiBr 7.4 2.822 312.07 128.6	55.32
44 Water/LiBr .68 2.822 316.96 128.6	54.61

ambient temperature sometimes cause system performance improve or decline. The effects of variations in ambient temperature on the overall exergy efficiency of the multigeneration system and its subsystems are shown in Fig. 3. It is observed that, as the ambient temperature increases from 270 K to 320 K, the overall exergy efficiency changes from 40.6% to 38.9% for the multigeneration system, from 51.5% to 60.0% for Rankine Cycle 1, from 16.7% and 21.4% for Rankine Cycle 2, from 38.9% to 40.7% for Gas Turbine Cycle 2, from 44.4% to 7.9% for the hot water heater, and from 28.3% to 3.8% for the hot air heater. The exergy efficiency of Gas Turbine Cycle 1 remains constants at 31.0% as the ambient temperature varies over the same range. Note that the overall exergy efficiency of the multigeneration system decreases as the ambient temperature increases while the exergy efficiencies of Rankine Cycle 1, Rankine Cycle 2 and Gas Turbine Cycle 2 increase. This observation is somewhat explained by the fact that the values of the exergy efficiencies for the hot water and hot air heaters decrease by more than the values of exergy efficiencies for Rankine Cycle 1, Rankine Cycle 2 and Gas Turbine Cycle 2 increase, resulting in a decrease in the overall exergy efficiency of the multigeneration system.

Correspondingly, the effects of varying ambient temperature on the overall energy efficiency of the multigeneration system and its subsystems are shown Fig. 4. It is seen that the ambient temperature generally does not affect the

Table 3 Input and output values of important components.

Component	Value
Gas Turbine 1	45.25 MW
Gas Turbine 2	4.67 MW
Rankine Turbine 1	4.88 MW
Rankine Turbine 2	4.04 MW
Work input of Compressor 1	8.3 MW
Work input of Compressor 2	2.92 MW
Work input of Pump 1	61.69 kW
Work input of Pump 2	25.2 kW
Heliostat aperture area	5000 m^2
Direct normal irradiation	850 W/m ²



Fig. 2. Exergy destruction rates of selected units of the multigeneration system.



Fig. 3. Variation with ambient temperature of the exergy efficiency of the overall multigeneration system and selected subsystems.

overall energy efficiency of the multigeneration system and its subsystems. Fig. 5 shows the effects of varying of ambient temperature on the overall energy and exergy efficiencies of the multigeneration system as well as on the cycles driven solely by biomass or solar energy. It is clear



Fig. 4. Variation with ambient temperature of the energy efficiency of the overall multigeneration system and selected subsystems.



Fig. 5. Variation with ambient temperature of the energy and exergy efficiencies of the overall multigeneration system when it is operated solely on either biomass or solar energy or in an integrated manner on both renewable energy sources.

from the figure that the changes in reference temperature do affect neither the overall energy efficiency of the multigeneration system nor the cycles driven solely by biomass or solar energy. When the ambient temperature changes from 273 K to 320 K, the overall exergy efficiencies of the multigeneration system and of the cycle driven solely biomass energy decrease from 40.6% to 38.9% and from 38.6% to 36.8% respectively, while the exergy efficiency of the cycle driven solely by solar energy increases from 40.5% to 47.6%.

4.2. Effect of combustion temperature

Combustion temperature plays an important role in the performance of Gas Turbine Cycle 1 and the overall multigeneration system. Fig. 6 shows the effect of variations in combustion temperature on the exergy efficiencies of the overall multigeneration system and its subsystems. When the combustion temperature rises from 1500 K to 1700 K, the system overall exergy efficiency increases from 37.0% to 42.3% while the exergy efficiency of Gas Turbine Cycle 1 increases from 28.3% to 33.7%. Over the same combustion temperature rise, the exergy efficiencies of Rankine



Fig. 6. Variation with combustion temperature (T_5) of the exergy efficiency of the overall multigeneration system and selected subsystems.



Fig. 7. Variation with combustion temperature (T_5) of the energy efficiency of the overall multigeneration system and selected subsystems.

Cycle 1, Rankine Cycle 2, Gas Turbine Cycle 2, and the hot air heater change from 59.9% to 53.1%, 21.4% to 18.0%, 47.0% to 44.0% and 14.7% to 17.0%, respectively. No effect is observed on the exergy efficiency of the hot water heater when the combustion temperature changes from 1500 K to 1700 K. It is noted that the exergy efficiencies of all subsystems except for Gas Turbine Cycle 1 and hot air heater decrease over the considered combustion temperature change, but the overall exergy efficiency nevertheless increases. This is in part because the power output of Gas Turbine Cycle 1 is large relative to the power outputs of other subsystems, so when the power output of Gas Turbine Cycle 1 increases significantly it is the dominant factor affecting the change in the overall system exergy efficiency.

The effects of varying combustion temperature on the overall energy efficiency of the multigeneration system and its subsystems are shown in Fig. 7. When the combustion temperature rises from 1500 K to 1700 K, the overall energy efficiency of the multigeneration system increases from 63.3% to 69.9% while the energy efficiency of Gas Turbine Cycle 1 increases from 37.7% to 45.0%. Varying the combustion temperature has no effect of on the energy efficiencies of other subsystems.

4.3. Effect of compressor inlet temperature for Gas Turbine Cycle 1

The compressor inlet temperature for Gas Turbine Cycle 1 plays an important role in its net power output, and hence on the power output of the overall system, so it is investigated here. The effect of varying the compressor inlet temperature for Gas Turbine Cycle 1 on the exergy efficiency of the overall system and its subcycles is illustrated in Fig. 8. When the compressor inlet temperature is raised from 273 K to 373 K, the overall exergy efficiency of Gas Turbine Cycle 1 declines from 31.7% to 29.1% and the exergy efficiencies of other subsystems remain unchanged.

Fig. 9 shows the variation of overall energy efficiency of the multigeneration system and its subsystems with changing compressor inlet temperature for Gas Turbine Cycle 1. When the compressor inlet temperature is increased from 273 K to 373 K, the overall energy efficiency of the multigeneration system decreases from 67.2% to 64.1%, while the corresponding energy efficiency of Gas Turbine Cycle 1 decreases from 42.2% to 38.8%, respectively. The changes in compressor inlet temperature have no effect on the energy efficiencies of the other subsystems.

4.4. Effect of inlet pressure of Gas Turbine 1

The inlet pressure to a Gas Turbine generally plays an important role on its performance as well as the overall system in which it operates. Fig. 10 shows the effect of varying the inlet pressure of Gas Turbine 1 on the exergy efficiency of the overall system and its subsystems. When the inlet pressure to Gas Turbine 1 rises from 400 kPa to 700 kPa, the exergy efficiency increases from 36.9% to 43.0% for the overall system and from 28.2% to 34.5% for Gas Turbine Cycle 1. The exergy efficiencies of Rankine Cycle 1, Rankine Cycle 2, Gas Turbine Cycle 2, and the hot air



Fig. 8. Variation with inlet temperature (T_2) to Compressor 1 of the exergy efficiency of the overall multigeneration system and selected subsystems.



Fig. 9. Variation with inlet temperature (T_2) to Compressor 1 of the energy efficiency of the overall multigeneration system and selected subsystems.



Fig. 10. Variation with inlet pressure (P_3) to Gas Turbine 1 of the exergy efficiency of the overall multigeneration system and selected subsystems.



Fig. 11. Variation with inlet pressure (P_3) to Gas Turbine 1 of the energy efficiency of the overall multigeneration system and selected subsystems.

heater also increase with this pressure change, from 52.9% to 62.2%, 17.9% to 23.3%, 44.0% to 47.9% and 17.1% to 14.9%, respectively. But the inlet pressure of Gas Turbine 1 is not observed to affect the exergy efficiency of the hot water heater.



Fig. 12. Variation with heliostat aperture area of the exergy efficiency of the overall multigeneration system and selected subsystems.



Fig. 13. Variation with heliostat aperture area of the overall energetic efficiency of the multigeneration system and selected subsystems.

The effect of varying the inlet pressure of Gas Turbine 1 on the energy efficiency of the overall system and its subsystems is shown in Fig. 11. When the inlet pressure of Gas Turbine 1 rises from 400 kPa to 700 kPa, the energy efficiency increases from 62.9% to 70.9% for the multigeneration system and from 37.6% to 46.0% for Gas Turbine Cycle 1 varies, but no variation is observed in the energy efficiencies of the other subsystems.

4.5. Effect of aperture area of the heliostat

Heliostat aperture area plays an important role in a solar assisted system because it directly relates to the energy and exergy input. Fig. 12 shows the effects of varying aperture area on the exergy efficiency of the overall multigeneration system and its subsystems. The exergy efficiency of the overall multigeneration system decreases from 40.5% to 38.4% when aperture area rises from 2000 m^2 to $10,000 \text{ m}^2$ while the exergy efficiencies of all subsystems remain unchanged. Correspondingly, Fig. 13 shows the effect of a variation in aperture area on the energy efficiency of the overall multigeneration system and its subsystems.



Fig. 14. Variation with direct normal irradiation of the overall exergetic efficiency of the multigeneration system and selected subsystems.

The energy efficiency of the overall multigeneration system declines from 68.3% to 63.6% when aperture area rises from 2000 m^2 to $10,000 \text{ m}^2$, and again the aperture area is seen to have no effect on the energy efficiencies of the subsystems.

4.6. Effect of direct normal irradiation (DNI)

Direct normal irradiation plays an important role in the concentrated solar panel since it directly relates to the energy and exergy input. Fig. 14 shows the effect of varying direct normal irradiation on the exergy efficiency of the overall multigeneration system and its subsystems. The exergy efficiency of the overall multigeneration system decreases from 40.4% to 39.4% when direct normal irradiation rises from 400 W/m² to 1000 W/m² while the exergy efficiencies of all subsystems remain unchanged.

5. Conclusions

A new renewable energy-based multigeneration system has been developed and investigated using exergy and energy analyses. The overall energy and exergy efficiencies respectively of the developed system using biomass and solar energy are 66.5% and 39.7%. However, the energy and exergy efficiencies respectively are only 64.5% and 37.6% when the biomass system operates alone, and only 27.3% and 44.3% when the solar system operates alone. These results demonstrate the system's efficiencies are lower when it operates on a single renewable energy source rather than in an integrated manner using two renewable energy sources.

References

- Ahmadi, P., Dincer, I., Rosen, M.A., 2013. Development and assessment of an integrated biomass-based multigeneration energy system. Energy 56, 155–166.
- Al-Sulaiman, F.A., Dincer, I., Hamdullahpur, F., 2012. Energy and exergy analyses of a biomass trigeneration system using an organic Rankine Cycle. Energy 45, 975–985.
- Chicco, G., Mancarella, P., 2008. A unified model for energy and environmental performance assessment of natural gas-fueled polygeneration systems. Energy Convers. Manage. 49, 2069–2077.
- Cohce, M.K., Dincer, I., Rosen, M.A., 2011. Energy and exergy analyses of a biomass-based hydrogen production system. Bioresour. Technol. 102 (18), 8466–8474.
- Dincer, I., Rosen, M.A., 2013. Exergy: Energy, Environment and Sustainable Development, second ed. Elsevier, Oxford, UK.
- Dincer, I., Zamfirescu, C., 2011. Sustainable Energy Systems and Applications. Springer.
- Dincer, I., Zamfirescu, C., 2012. Renewable-energy-based multigeneration systems. Int. J. Energy Res. 36, 1403–1415.
- Khaliq, A., 2009. Exergy analysis of gas turbine trigeneration system for combined production of power heat and refrigeration. Int. J. Refrig 32, 534–545.
- Khaliq, A., Kumar, R., Dincer, I., 2009. Performance analysis of an industrial waste heat-based trigeneration system. Int. J. Energy Res. 33, 737–744.
- Malico, I., Carvalhinho, A.P., Tenreiro, J., 2009. Design of a trigeneration system using a high-temperature fuel cell. Int. J. Energy Res. 33, 144– 151.
- Ozturk, M., Dincer, I., 2013. Thermodynamic assessment of an integrated solar power tower and coal gasification system for multigeneration purposes. Energy Convers. Manage. 76, 1061–1072.
- Ozturk, M., Dincer, I., 2013. Thermodynamic analysis of a solar-based multigeneration system with hydrogen production. Appl. Therm. Eng. 51, 1235–1244.
- Sami, M., Annamalai, K., Wooldridge, M., 2001. Co-firing of coal and biomass fuel blends. Prog. Energy Combust. Sci. 27, 171–214.
- Srinivas, T., Gupta, A.V.S.S.K.S., Reddy, B.V., 2007. Parametric simulation of steam injected gas turbine combined cycle. Proc. Inst. Mech. Eng., Part A: J. Power Energy 221, 873–882.
- Szargut, J., Morris, D.R., Steward, F.R., 1988. Exergy Analysis of Thermal, Chemical, and Metallurgical Processes. Hemisphere Publishing Corporation, New York.