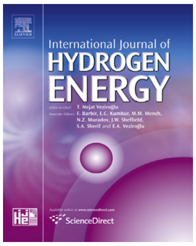
ARTICLE IN PRESS

INTERNATIONAL JOURNAL OF HYDROGEN ENERGY XXX (2017) 1–8

Available online at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/he



A novel multigenerational hydrogen production system: Performance evaluation

H. Rabbani*, I. Dincer, S. Rahnamayan

Faculty of Engineering and Applied Science, University of Ontario Institute of Technology (UOIT), 2000 Simcoe Street North, Oshawa, ON L1H 7K4, Canada

ARTICLE INFO

Article history:
Received 15 May 2016
Received in revised form
8 February 2017
Accepted 9 February 2017
Available online xxx

Keywords:
Hydrogen production
Solar energy
Energy
Exergy
Efficiency
Multigeneration

ABSTRACT

The current study discusses the first and second laws analyses of a multi-commodity solar energy-based integrated energy system. The system produces hydrogen in a sustainable manner and supplies 500 MW of electricity, hot water, and hot air for space heating for various applications in sectors. Energy and exergy losses of the plant components are calculated based on a thermodynamic model. Based on the total output work, both energy and exergy efficiencies of the overall system are determined. A parametric study is performed by varying inlet air temperature, air-to-fuel ratio, throttling temperature, and condenser temperature. The results show that increasing pressure ratio increases the efficiency from 66% to 68% over a range of 8–25. Increasing the air-to-fuel ratio increases the energy efficiency from 0.60 to above 0.80, respectively.

Introduction

Exergy (known as availability) is the maximum useful work measure. It is also a metric of energy, not only in quantity but also in quality. A standalone energy analysis is not sufficient to investigate irreversibility of a system, however, exergy counts on occurred irreversibility in a process. Exergy analysis is used to evaluate efficient use of energy in a power plant. Exergy is not a thermodynamics quantity; however it is depended on thermodynamics quantities (i.e., enthalpy and entropy); which is used widely since 1960 [1,2]. The main goal of doing exergy analysis for a power plant is to find the irreversibility in each component of the plant and trying to minimize them. Currently, exergy analyses have been adopted by many researchers for a huge number of industrial processes.

Ganapathy et al. [1] have performed an exergy analysis for a 50 MW combined power plant located in India. They found that major exergy losses take place in the condenser, however this energy cannot be used elsewhere. They also suggested modifications be made for the combustor due to high exergy loss. Horlock et al. [3] performed an exergy analysis for three different fossil fuel based power plants. They also considered that irreversibility takes places during combustion. Dincer and Rosen [3,7–13] have discussed exergy analysis for a variety of processes and system components. Sue and Chuang [4] have also discussed exergy analysis for a combustion gas in a

---

* *Corresponding author.*
E-mail addresses: hassan.rabbani@uoit.ca (H. Rabbani), Ibrahim.Dincer@uoit.ca (I. Dincer), shahryar.rahnamayan@uoit.ca (S. Rahnamayan).

http://dx.doi.org/10.1016/j.ijhydene.2017.02.068
0360-3199/© 2017 Hydrogen Energy Publications LLC. Published by Elsevier Ltd. All rights reserved.

Please cite this article in press as: Rabbani H, et al., A novel multigenerational hydrogen production system: Performance evaluation, International Journal of Hydrogen Energy (2017), http://dx.doi.org/10.1016/j.ijhydene.2017.02.068

Nomenclature

E	Energy, kJ
$\dot{E}$	Energy rate, kW
Ex	Exergy, kJ
ex	Specific exergy, kJ/kg
$\dot{E}x$	Exergy rate, kW
H	Total enthalpy, kJ
$\dot{H}$	Enthalpy rate, kW
h	Specific enthalpy, kJ/kg
$\dot{m}$	Mass flow rate, kg/s
Q	Heat, kJ
$\dot{Q}$	Heat rate, kW
s	Specific entropy, kJ/kg·K
$\dot{S}$	Heat rate, kW
T	Temperature, K
P	Pressure, Pa
P_o	Reference-environment pressure, Pa
$\dot{W}$	Work rate, kW

Subscripts

Ch	Chemical
Dest	Destruction
En	Energy
Ex	Exergy
o	Reference

Greek letters

Δ	Difference
η	Efficiency

turbine based power generation system. Their results show that exergy analysis calculates the plant efficiency more accurately. Abdul Khaliq [5] discussed the exergy analysis of a gas turbine tri-generation system. His results show that maximum exergy is destroyed during steam generation and the exergy destruction, when combustion decreases because of an increase in the pressure ratio. Haseli et al. [6] have discussed thermodynamics analysis for a combined gas turbine power plant with a solid oxide fuel cell. Their results show that increasing the compressor inlet temperature decreases both energy and exergy efficiencies for both conventional and SOFC power plants. However, a gas turbine with SOFC has a 26.6% higher exergetic performance. Rabbani et al. [14] have discussed energy and exergy analysis of a solar based integrated system. In another study, they have also discussed wind turbine based combined cycles [15]. They have also studied hydrogen production systems coupled with different energy systems [16–19].

AlZahrani and Dincer [20] have performed design and analysis of a solar tower based integrated system using high temperature electrolyzer for hydrogen production. His system analysis showed 12.7% solar to hydrogen efficiency. Sarrias-Mena et al. [21] has developed electrolyzer models for hydrogen production from wind energy systems. They developed four electrolyzer models for hydrogen production from wind energy systems and evaluated their performance. They compared the response of each of the model under variable wind speed and grid demand. Khalid et al. [22] have performed comparative assessment of two integrated hydrogen energy systems using electrolyzers and fuel cells. Cilogullarıa et al. [23] have done investigation of hydrogen production performance of a photovoltaic (PV) and thermal system. Using exergy analysis he showed that PV/T based hydrogen production systems have higher energy and exergy efficiency and they are more cost effective. Yilmaz et al. [24] have done exergo-economic evaluation of hydrogen production powered by combined flash-binary geothermal power plant. His result showed that the unit exergetic cost of electricity from the power plant is 11.1 $/GJ (or 0.0400 $/kWh) and the unit exergetic cost of hydrogen is 26.1 $/GJ (or 3.14 $/kg H_2). Kalincia et al. [25] have done performance assessment of hydrogen production from a solar-assisted biomass gasification system. They reported energy and exergy efficiency of 27.29% and 23.92%, respectively. Various additional researchers [e.g., [26–34]] have analyzed and evaluated numerous hydrogen production based integrated energy systems both energetically and exergetically.

The aim of the present study is to thermodynamically analyze a new solar energy-based multigeneration system which produces heat, electricity, hot water, and hot air for space heating for various sectors. Energy and exergy analyses of the proposed system are conducted, and the effects of several different parameters are studied on overall energy and exergy efficiencies of the system.

System description

Fig. 1 shows the multi generation system used in the current study. This system is designed to supply 500 MW of electricity, hot water, hot air for space heating, and excess electricity can be used for hydrogen production. Air and fuel (methane in this study) are combust in combustion chamber and expanded in a gas turbine to produce mechanical work output which is converted to electrical work by an electricity generator. The high temperature and low pressure exhaust gases then are used to heat the high pressure water in steam Rankine cycle by using heat recovery heat exchanger (HX-1). The heat rejected by the condenser (HX-2) in the Rankine cycle is recovered by heating another stream of water. A part of this heated water is used in electrolyzer and other part is used as a hot water supply for residential use after passing through HX-4. Another stream of water acting as a coolant passes though HX-4 and is used in heat pump where R-134a is utilized as a working fluid. Air is heated in the heat pump system and it is used in space heating. In summary, the present system has four outputs, namely, electricity, hot water, space heating and hydrogen for utilization and deployment in various sectors.

Thermodynamic modeling

Each component in the plant has been analyzed separately; four equations have been written for each component, including enthalpy, entropy, and exergy. The basic exergy equation is

Please cite this article in press as: Rabbani H, et al., A novel multigenerational hydrogen production system: Performance evaluation, International Journal of Hydrogen Energy (2017), http://dx.doi.org/10.1016/j.ijhydene.2017.02.068

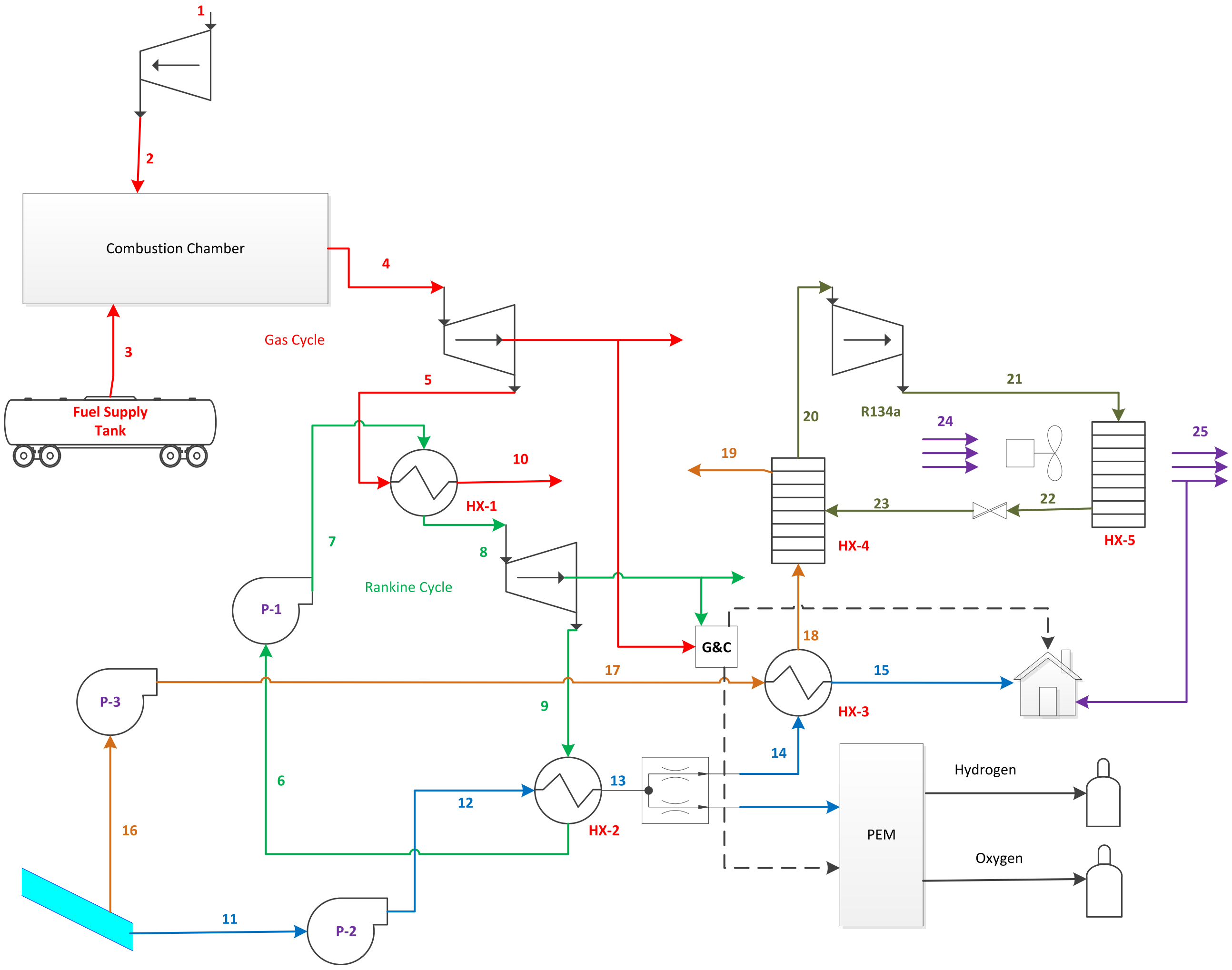


Fig. 1 – A new multi-commodities energy system.

$$Ex = \dot{m}((h - h_o) - T_o(s - s_o)) \quad (1)$$

Where h_o and s_o are calculated for both the fuel and air loops at 25 °C and at 101.325 kPa.

The main assumptions adopted for the simulation are listed as follows:

- The electrical power requirement for the community is 500 MW.
- Steady state operation is assumed for the plant components.
- The heat exchanger, pump (P), compressor (Comp) and turbines are adiabatic.
- Kinetic and potential exergetic terms are neglected for all system components.
- The ambient temperature and pressure are constant (i.e., $T_0 = 298$ K and $P_0 = 100$ kPa).
- Air is treated as an ideal gas with a molar composition of 21% oxygen and 79% nitrogen.
- The isentropic efficiency of the turbines, compressor and pump is 80%.

The mass, energy, entropy and exergy equations for each of the component are written as follows:

Compressor (1–2)

The mass, energy, entropy and exergy balance equations for the compressor are given as follows:

$$\dot{m}_1 = \dot{m}_2 \quad (2a)$$

$$\dot{m}_1 h_1 + \dot{W}_1 = \dot{m}_2 h_2 \quad (2b)$$

$$\dot{m}_1 s_1 + \dot{S}_{g_1} = \dot{m}_2 s_2 \quad (2c)$$

$$\dot{m}_1 ex_1 + \dot{W}_1 = \dot{m}_2 ex_2 + \dot{E}_{dest_{Comp,1}} \quad (2d)$$

Combustion chamber (2–3–4)

The mass, energy, entropy and exergy balance equations for the combustion chamber are given as follows:

Please cite this article in press as: Rabbani H, et al., A novel multigenerational hydrogen production system: Performance evaluation, International Journal of Hydrogen Energy (2017), http://dx.doi.org/10.1016/j.ijhydene.2017.02.068

$$\dot{m}_2 + \dot{m}_3 = \dot{m}_4 \tag{3a}$$

$$\dot{m}_2 h_2 + \dot{m}_3 h_3 = \dot{m}_4 h_4 \tag{3b}$$

$$\dot{m}_2 s_2 + \dot{m}_3 s_3 = \dot{m}_4 s_4 \tag{3c}$$

$$\dot{m}_2 ex_2 + \dot{m}_3 ex_3 = \dot{m}_4 ex_4 + \dot{E}_{dest_{CC}} \tag{3d}$$

Gas turbine (4–5)

The mass, energy, entropy and exergy balance equations for the gas turbine are given as follows:

$$\dot{m}_4 = \dot{m}_5 \tag{4a}$$

$$\dot{m}_4 h_4 = \dot{m}_5 h_5 + \dot{W}_{GT} \tag{4b}$$

$$\dot{m}_4 s_4 + \dot{S}_{g,GT} = \dot{m}_5 s_5 \tag{4c}$$

$$\dot{m}_4 ex_4 = \dot{m}_5 ex_5 + \dot{E}_{dest_{GT}} + \dot{W}_{GT} \tag{4d}$$

HX-1 (5–7–8–10)

The mass, energy, entropy and exergy balance equations for the HX-1 are given as follows:

$$\dot{m}_5 + \dot{m}_7 = \dot{m}_8 + \dot{m}_{10} \tag{5a}$$

$$\dot{m}_5 h_5 + \dot{m}_7 h_7 = \dot{m}_8 h_8 + \dot{m}_{10} h_{10} \tag{5b}$$

$$\dot{m}_5 s_5 + \dot{m}_7 s_7 + \dot{S}_{g,HX-1} = \dot{m}_8 s_8 + \dot{m}_{10} s_{10} \tag{5c}$$

$$\dot{m}_5 ex_5 + \dot{m}_7 ex_7 = \dot{m}_8 ex_8 + \dot{m}_{10} ex_{10} + \dot{E}_{dest_{HX-1}} \tag{5d}$$

Pump-1 (6–7)

The mass, energy, entropy and exergy balance equations for the Pump-1 are given as follows:

$$\dot{m}_6 = \dot{m}_7 \tag{6a}$$

$$\dot{m}_6 h_6 + \dot{W}_{P1} = \dot{m}_7 h_7 \tag{6b}$$

$$\dot{m}_6 s_6 + \dot{S}_{g,P1} = \dot{m}_7 s_7 \tag{6c}$$

$$\dot{m}_6 ex_6 + \dot{W}_{P1} = \dot{m}_7 ex_7 + \dot{E}_{dest_{P1}} \tag{6d}$$

Steam turbine (8–9)

The mass, energy, entropy and exergy balance equations for the stream turbine are given as follows:

$$\dot{m}_8 = \dot{m}_9 \tag{7a}$$

$$\dot{m}_8 h_8 = \dot{m}_9 h_9 + \dot{W}_{ST} \tag{7b}$$

$$\dot{m}_8 s_8 + \dot{S}_{g,ST} = \dot{m}_9 s_9 \tag{7c}$$

$$\dot{m}_8 ex_8 = \dot{m}_9 ex_9 + \dot{E}_{dest_{ST}} + \dot{W}_{ST} \tag{7d}$$

Condenser (12–9–6–13)

The mass, energy, entropy and exergy balance equations for the condenser are given as follows:

$$\dot{m}_{12} + \dot{m}_9 = \dot{m}_6 + \dot{m}_{13} \tag{8a}$$

$$\dot{m}_{12} h_{12} + \dot{m}_9 h_9 = \dot{m}_6 h_6 + \dot{m}_{13} h_{13} \tag{8b}$$

$$\dot{m}_{12} s_{12} + \dot{m}_9 s_9 + \dot{S}_{g,HX-2} = \dot{m}_6 s_6 + \dot{m}_{13} s_{13} \tag{8c}$$

$$\dot{m}_{12} ex_{12} + \dot{m}_9 ex_9 = \dot{m}_6 ex_6 + \dot{m}_{13} ex_{13} + \dot{E}_{dest_{HX-2}} \tag{8d}$$

Pump-2 (11–12)

The mass, energy, entropy and exergy balance equations for the Pump-2 are given as follows:

$$\dot{m}_{11} = \dot{m}_{12} \tag{9a}$$

$$\dot{m}_{11} h_{11} + \dot{W}_{P2} = \dot{m}_{12} h_{12} \tag{9b}$$

$$\dot{m}_{11} s_{11} + \dot{S}_{g,P2} = \dot{m}_{12} s_{12} \tag{9c}$$

$$\dot{m}_{11} ex_{11} + \dot{W}_{P2} = \dot{m}_{12} ex_{12} + \dot{E}_{dest_{P2}} \tag{9d}$$

Pump-3 (16–17)

The mass, energy, entropy and exergy balance equations for the Pump-3 are given as follows:

$$\dot{m}_{16} = \dot{m}_{17} \tag{10a}$$

$$\dot{m}_{16} h_{16} + \dot{W}_{P2} = \dot{m}_{17} h_{17} \tag{10b}$$

$$\dot{m}_{16} s_{16} + \dot{S}_{g,P3} = \dot{m}_{17} s_{17} \tag{10c}$$

$$\dot{m}_{16} ex_{16} + \dot{W}_{P3} = \dot{m}_{17} ex_{17} + \dot{E}_{dest_{P3}} \tag{10d}$$

HX-3 (17–14–15–14)

The mass, energy, entropy and exergy balance equations for the HX-3 are given as follows:

$$\dot{m}_{17} + \dot{m}_{14} = \dot{m}_{15} + \dot{m}_{18} \tag{11a}$$

$$\dot{m}_{17} h_{17} + \dot{m}_{14} h_{14} = \dot{m}_{15} h_{15} + \dot{m}_{18} h_{18} \tag{11b}$$

$$\dot{m}_{17} s_{17} + \dot{m}_{14} s_{14} + \dot{S}_{g,HX-3} = \dot{m}_{15} s_{15} + \dot{m}_{18} s_{18} \tag{11c}$$

$$\dot{m}_{17} ex_{17} + \dot{m}_{14} ex_{14} = \dot{m}_{15} ex_{15} + \dot{m}_{18} ex_{18} + \dot{E}_{dest_{HX-3}} \tag{11d}$$

HX-4 (18–23–20–19)

The mass, energy, entropy and exergy balance equations for the HX-4 are given as follows:

Please cite this article in press as: Rabbani H, et al., A novel multigenerational hydrogen production system: Performance evaluation, International Journal of Hydrogen Energy (2017), http://dx.doi.org/10.1016/j.ijhydene.2017.02.068

$$\dot{m}_{18} + \dot{m}_{23} = \dot{m}_{20} + \dot{m}_{19} \tag{12a}$$

$$\dot{m}_{18}h_{18} + \dot{m}_{23}h_{23} = \dot{m}_{20}h_{20} + \dot{m}_{19}h_{19} \tag{12b}$$

$$\dot{m}_{18}s_{18} + \dot{m}_{23}s_{23} + \dot{S}_{g,HX-4} = \dot{m}_{20}s_{20} + \dot{m}_{19}s_{19} \tag{12c}$$

$$\dot{m}_{18}ex_{18} + \dot{m}_{23}ex_{23} = \dot{m}_{20}ex_{20} + \dot{m}_{19}ex_{19} + \dot{E}_{dest_{HX-4}} \tag{12d}$$

HX-5 (21–24–22–25)

The mass, energy, entropy and exergy balance equations for the HX-5 are given as follows:

$$\dot{m}_{21} + \dot{m}_{24} = \dot{m}_{22} + \dot{m}_{25} \tag{13a}$$

$$\dot{m}_{21}h_{21} + \dot{m}_{24}h_{24} = \dot{m}_{22}h_{22} + \dot{m}_{25}h_{25} \tag{13b}$$

$$\dot{m}_{21}s_{21} + \dot{m}_{24}s_{24} + \dot{S}_{g,HX-5} = \dot{m}_{22}s_{22} + \dot{m}_{25}s_{25} \tag{13c}$$

$$\dot{m}_{21}ex_{21} + \dot{m}_{24}ex_{24} = \dot{m}_{22}ex_{22} + \dot{m}_{25}ex_{25} + \dot{E}_{dest_{HX-5}} \tag{13d}$$

Compressor-2 (20–21)

The mass, energy, entropy and exergy balance equations for the Compressor-2 are given as follows:

$$\dot{m}_{20} = \dot{m}_{21} \tag{14a}$$

$$\dot{m}_{20}h_{20} + \dot{W}_{Comp2} = \dot{m}_{21}h_{21} \tag{14b}$$

$$\dot{m}_{20}s_{20} + \dot{S}_{g,Comp2} = \dot{m}_{21}s_{21} \tag{14c}$$

$$\dot{m}_{20}ex_{20} + \dot{W}_{Comp2} = \dot{m}_{21}ex_{21} + \dot{E}_{dest_{Comp2}} \tag{14d}$$

The net work output (in kW)of turbine work is calculated as

$$\dot{W}_{net} = \sum \dot{W}_{turbine} - \sum \dot{W}_{pump} - \sum \dot{W}_{compressors} \tag{15}$$

As there are four outputs for this system, the net energy efficiency can be defined as

$$\eta_{th} = \frac{\dot{W}_{net} + \dot{m}_{H_2}HHV_{H_2} + \dot{Q}_{Hot-Water} + \dot{Q}_{Heat}}{\dot{m}_f HHV_f} \tag{16}$$

where

$$\dot{Q}_{Hot-Water} = \dot{m}_{14}(h_{14} - h_{15}) \tag{17}$$

$$\dot{Q}_{Heat} = \dot{m}_{24}(h_{25} - h_{24}) \tag{18}$$

Exergy efficiency is the ratio of net work over chemical content of the fuel.

$$\eta_{ex} = \frac{\dot{W}_{net} + \dot{m}_{H_2}ex^{ch}_{H_2} + \dot{E}x_{Hot-Water} + \dot{E}x_{Heat}}{\dot{m}_1 exf_{ch}} \tag{19}$$

Where

$$\dot{E}x_{Hot-Water} = \dot{m}_{14}(ex_{14} - ex_{15}) \tag{20}$$

$$\dot{E}x_{Heat} = \dot{m}_{24}(ex_{25} - ex_{24}) \tag{21}$$

Results and discussion

Fig. 2 shows the effect of compressor ratio on energy and exergy efficiency of the plant. Increasing the compressor ratio increases the plant efficiency due to increase in output work by the gas turbine. The excess electricity is used to produce hydrogen. However, increasing the pressure ratio also increases the work input required by the compressor which somewhat the excess power generation by the gas turbine. Changing the compressor ratio changes the energy efficiency from 66% to above 68%. The change in exergy efficiency with respect to change in compressor ratio is small. The change is just 2% over a compressor ratio of 5–25. This suggests that exegetically and economically it may not be a very wise decision to use a large compressor.

Fig. 3 shows the effect of air to fuel ratio. The trend is linear. Increasing the air to fuel ratio increases both energy and exergy efficiencies. The energy exergy efficiency changes from 60% to 83% which represents a significant increase. The net output power increases with increase in air to fuel ratio. However, due to a large exergy destruction in combustion chamber with increase in air to fuel ratio, the change in exergy efficiency is comparatively small. The exergy efficiency changes from 59.5% to around 62%.

Fig. 4 illustrates the effect of Rankine cycle (i.e., steam turbine inlet temperature) on the energy efficiency and net work output. Increasing the temperature, although, increases the output power from steam turbine but due to large exergy destruction across turbine and less available energy for hot water and space heating; therefore, the overall energy and exergy efficiencies decrease. The energy efficiency changes from 65.1% to around 65.8%, respectively. While the exergy efficiency changes from 59.1% to 59.5%. The change in efficiency is very small which suggests that the plant can be operated in the temperature range of 600 K–800 K. However, operating at higher temperature may result a higher negative economic impact without any significant increase in the overall efficiency of the plant.

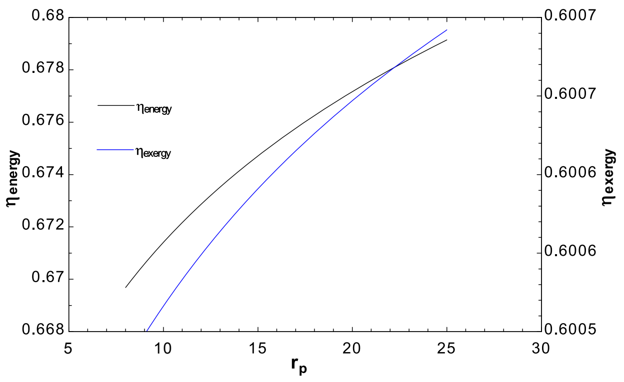


Fig. 2 – Effects of compressor ratio on energy and exergy efficiencies.

Please cite this article in press as: Rabbani H, et al., A novel multigenerational hydrogen production system: Performance evaluation, International Journal of Hydrogen Energy (2017), http://dx.doi.org/10.1016/j.ijhydene.2017.02.068

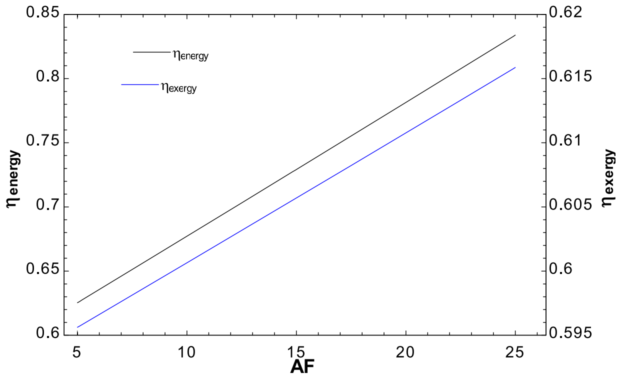


Fig. 3 – Effects of air to fuel ratio on energy and exergy efficiencies.

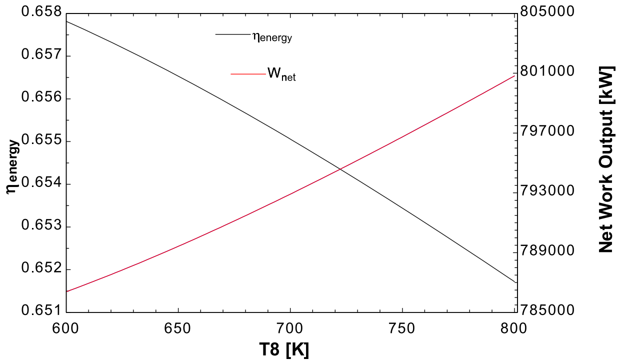


Fig. 4 – Effects of steam turbine inlet temperature on energy efficiency and net work output.

Decreasing the hot water supply temperature actually decreases both energy and exergy efficiency of the system. Because the condenser ejects more energy than actually utilized amount which results decrease in efficiency of the plant. Fig. 5 shows the effect of hot water temperature on the energy and exergy efficiency of the system. The effect on energy efficiency is quite dominant and energy efficiency decreases linearly from 78% to 64%. While the change in exergy efficiency is quite negligible (i.e., 0.5%).

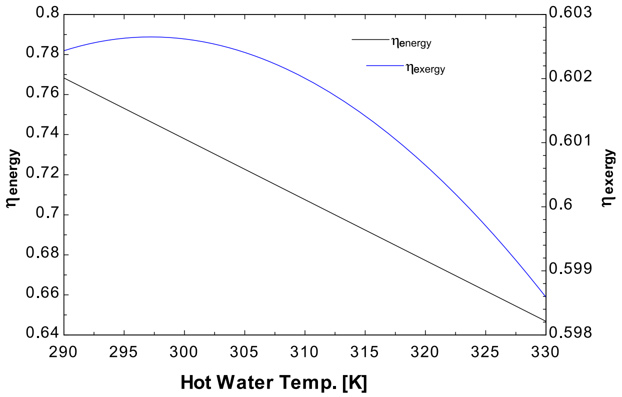


Fig. 5 – Effects of hot water supply temperature on energy and exergy efficiencies.

Fig. 6 indicates the effect of varying throttling temperature on exergy efficiency. Increasing the throttling temperature increases the energy efficiency and vice versa. The change is very small which accounts for only 0.1%. The energy and exergy efficiencies decrease initially with a sudden increase and decrease from 270 K onward. While the exergy efficiency increases with an increase in temperature.

Fig. 7 presents the effect of ambient temperature on energy and exergy efficiencies of the system. The energy and exergy

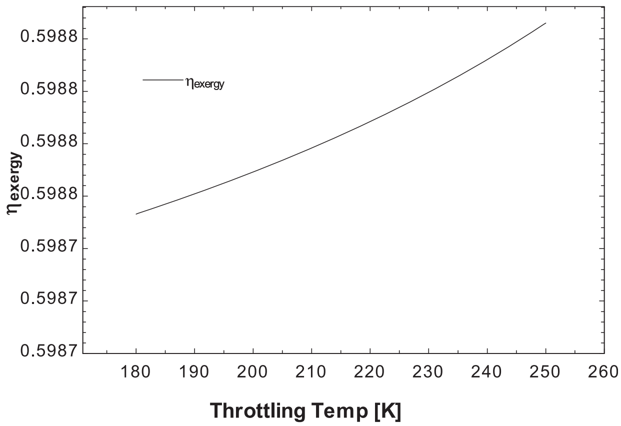


Fig. 6 – Effects of throttling temperature on energy and exergy efficiencies.

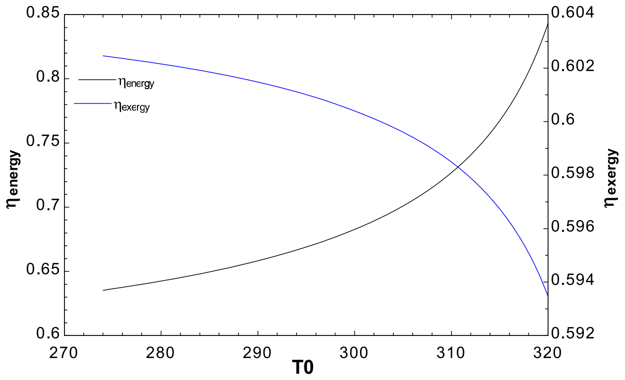


Fig. 7 – Effects of surrounding temperature on energy and exergy efficiencies.

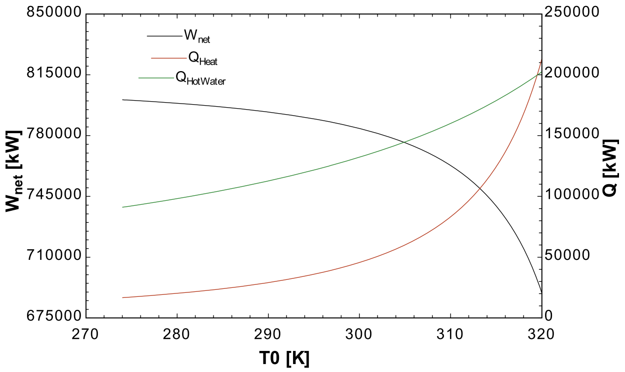


Fig. 8 – Effects of ambient temperature on plant work output, space heating and hot water supply.

Please cite this article in press as: Rabbani H, et al., A novel multigenerational hydrogen production system: Performance evaluation, International Journal of Hydrogen Energy (2017), http://dx.doi.org/10.1016/j.ijhydene.2017.02.068

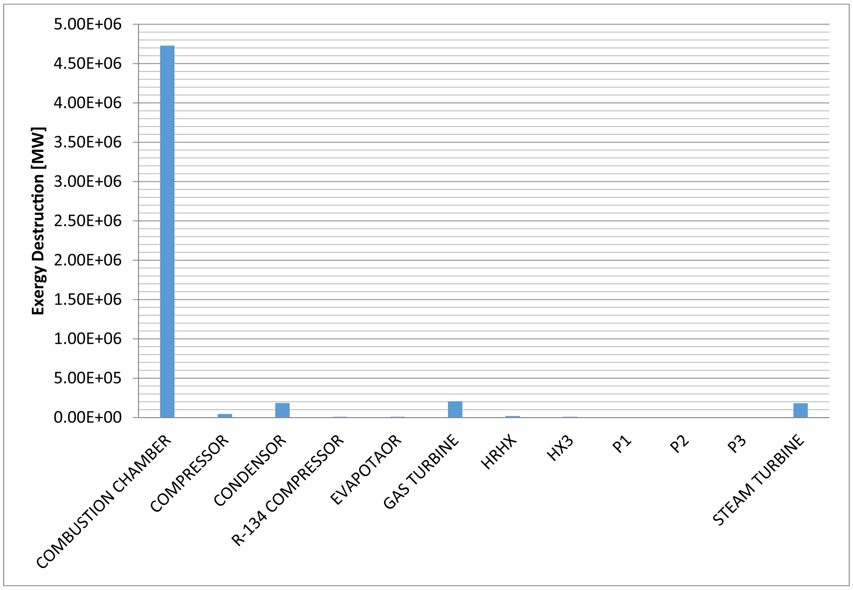


Fig. 9 – **Exergy destruction across different components.**

efficiencies show completely opposite trends. With increase in ambient temperature, the energy efficiency increases sharply from 60% to around 80%. This increase is due to the cumulative increase of hot water supply and space heating. If the temperature difference between the ambient and required space heating and hot water supply is lower, then higher flow rates of hot water and air can be supplied. This actually results increase in energy efficiency of the system. It is also important to notice that increasing the ambient temperature actually decreases the work output of the plant as that is why many gas turbine plants have air inlet cooling system installed with them. Fig. 8 shows the effect of ambient temperature on net work output and heat utilized for water and space heating.

Fig. 9 illustrates the exergy destruction across different components of the system. The highest exergy destruction is across combustion chamber. The exergy destruction across steam turbine and gas turbine is also quite noticeable. The results of this study shown in Fig. 9 are consistent well with a similar system considered by Ameri et al. [35].

Conclusions

In the present study, exergy analysis of a multi generation system is conducted. Energy and exergy losses of the different plant components have been estimated based on the thermodynamics model. Based on the total work output, energy and exergy efficiencies have been determined. A parametric study has been performed by varying inlet air temperature, air to fuel ratio, throttling temperature, and condenser temperature. The following conclusions are extracted from this study:

- Increasing pressure ratio increases the efficiency from 66% to 68% over a range of 8–25. Increasing the air to fuel ratio increases the energy efficiency from 0.60 to above 0.80.
- With increase in ambient temperature, the energy efficiency increases sharply from 60% to around 80%.
- The energy and exergy efficiencies decrease initially with a sudden increase and decreases from 270 K to onward. While the exergy efficiency increases with increase in temperature.
- Due to large exergy destruction in combustion chamber with increase in air to fuel ratio, the change in exergy efficiency is comparatively small. The exergy efficiency changes from 59.5% to around 62%.
- Increasing the air to fuel ratio increases both energy and exergy efficiencies. The energy exergy efficiency changes from 60% to 83% which indicates a significant increase.

REFERENCES

[1] Ganapathy T., Alagumurthi N., Gakkharand R.P, Murugesan K. Exergy analysis of operating lignite fired thermal power plant.

[2] Dincer Ibrahim, Rosen Marc A. EXERGY: Energy, Environment and Sustainable Development [Hardcover].

[3] Horlock JH, Young JB, Manfrida G. Exergy analysis of modern fossil–fuel power plants. J Eng Gas Turbines Power Jan. 2000;122:1–7.

[4] Sue Deng-Chern, Chuang Chia-Chin. Engineering design and exergy analyses for combustion gas turbine based power generation system. Energies 2015;8(12):12418.

[5] Khaliq Abdul. Exergy analysis of gas turbine trigeneration system for combined production of power heat and refrigeration. Int J Refrig May 2009;32(3):534–45.

[6] Haseli Y, Dincer I, Naterer GF. Thermodynamic analysis of a combined gas turbine power system with a solid oxide fuel cell through exergy. Thermochim Acta 15 December 2008;480(1–2):1–9.

[7] Orhan Mehmet F, dincer Ibrahim, Rosen Marc A. Exergoeconomic analysis of a thermochemical

Please cite this article in press as: Rabbani H, et al., A novel multigenerational hydrogen production system: Performance evaluation, International Journal of Hydrogen Energy (2017), http://dx.doi.org/10.1016/j.ijhydene.2017.02.068

copper–chlorine cycle for hydrogen production using specific exergy cost (SPECO) method. Original Research Article Thermochim Acta 10 January 2010;497(1–2):60–6.
[8] Orhan Mehmet F, Dincer Ibrahim, Rosen Marc A. An exergy–cost–energy–mass analysis of a hybrid copper–chlorine thermochemical cycle for hydrogen production. Original Research Article Int J Hydrogen Energy May 2010;35(10):4831–8.
[9] Rosen Marc A, Dincer Ibrahim, Kanoglu Mehmet. Role of exergy in increasing efficiency and sustainability and reducing environmental impact. Original Research Article Energy Policy January 2008;36(1):128–37.
[10] Dincer Ibrahim, Hussain MM, Al-Zaharnah I. Energy and exergy use in public and private sector of Saudi Arabia. Energy Policy September 2004;32(14):1615–24. Original Research Article.
[11] Ozgener L, Hepbasli Arif, Dincer Ibrahim. Energy and exergy analysis of the Gonen geothermal district heating system, Turkey. Geothermics October 2005;34(5):632–45. Original Research Article.
[12] Dincer Ibrahim. Exergy as a potential tool for sustainable drying systems. Original Research Article Sustain Cities Soc 22 April 2011. In Press, Corrected Proof, Available online.
[13] Haseli Y, Dincer Ibrahim, Naterer GF. Optimum temperatures in a shell and tube condenser with respect to exergy. Int J Heat Mass Transf May 2008;51(9–10):2462–70. Original Research Article.
[14] Rabbani M, Ratlamwala TAH, Dincer I. Transient energy and exergy analyses of a solar based integrated system (8 pages), Paper No: SOL-13–1354 J Sol Energy Eng Aug 25, 2014;137(1):011010. http://dx.doi.org/10.1115/1.4028072. June 08, 2014.
[15] Rabbani M, Dincer I, Naterer GF. Thermodynamic assessment of a wind turbine based combined cycle. Energy 2012;44(1):321–8.
[16] Rabbani M, Dincer I. Energetic and exergetic assessments of glycerol steam reforming in a combined power plant for hydrogen production. Int J Hydrogen Energy 14 September 2015;40(34):11125–32.
[17] Rabbani M, Ratlamwala TAH, Dincer I. Transient energy and exergy analyses of a solar based integrated system. ASME J Sol Energy Eng Incl Wind Energy Build Energy Conserv 2014. http://dx.doi.org/10.1115/1.4028072.
[18] Rabbani M, Dincer I, Naterer G. Electrochemical modeling of a photo electrochemical chloralkali reactor. J Chem Eng Process Process Intensif 2014;82:42–53.
[19] Rabbani M, Dincer I, Naterer G. Thermodynamic assessment of a wind turbine based combined cycle. J Energy August 2012;44(1):321–8.
[20] AlZahrania AA, Dincer I. Design and analysis of a solar tower based integrated system using high temperature electrolyzer for hydrogen production. Int J Hydrogen Energy 25 May 2016;41(19):8042–56. Special Issue on Progress in Hydrogen Production and Applications (ICH2P-2015), 3–6 May 2015, Oshawa, Ontario, Canada.
[21] Sarrias-Mena R, Fernández-Ramírez LM, García-Vázquez CA, Jurado F. Electrolyzer models for hydrogen production from wind energy systems. Int J Hydrogen Energy 23 February 2015;40(7):2927–38.
[22] Khalid F, Aydin M, Dincer I, Rosen MA. Comparative assessment of two integrated hydrogen energy systems using electrolyzers and fuel cells. Int J Hydrogen Energy 26 November 2016;41(44):19836–46.
[23] Cilogulları M, Erden M, Karakilcik M, Dincer I. Investigation of hydrogen production performance of a photovoltaic and thermal system. Int J Hydrogen Energy 26 January 2017;42(4):2547–52.
[24] Yilmaz C, Kanoglu M, Abusoglu A. Exergetic cost evaluation of hydrogen production powered by combined flash-binary geothermal power plant. Int J Hydrogen Energy 26 October 2015;40(40):14021–30.
[25] Kalincia Y, Hepbaslib A, Dincer I. Performance assessment of hydrogen production from a solar-assisted biomass gasification system. Int J Hydrogen Energy 10 May 2013;38(14):6120–9.
[26] Ratlamwala TAH, Gadalla MA, Dincer I. Performance assessment of an integrated PV/T and triple effect cooling system for hydrogen and cooling production. Int J Hydrogen Energy 2011;36(17):11282–91.
[27] Gadalla MA, Ratlamwala TAH, Dincer I. Energy and exergy analyses of an integrated fuel cell and absorption cooling system. Int J Exergy 2010;7(6):731–54.
[28] Ratlamwala TAH, Dincer I, Gadalla MA. Performance analysis of a novel integrated geothermal-based system for multi-generation applications. Appl Therm Eng 2012;40:71–9.
[29] Ratlamwala TAH, El-Sinawi AH, Gadalla MA. Performance analysis of a new designed PEM fuel cell. A Aidan Int J Energy Res 2012;36(11):1121–32.
[30] Rabbani M, Dincer I, Naterer GF, Aydin M. Determining parameters of heat exchangers for heat recovery in a Cu–Cl thermochemical. Int J Hydrogen Energy Hydrogen Prod Cycle August 2012;37(15):11021–34.
[31] Ratlamwala TAH, Dincer I. Energy and exergy analyses of a Cu–Cl cycle based integrated system for hydrogen production. Chem Eng Sci 2012;84:564–73.
[32] Rabbani M, Dincer I, Naterer GF. Efficiency assessment of a photo electrochemical chloralkali process for hydrogen and sodium hydroxide production. Int J Hydrogen Energy 4 February 2014;39(5):1941–56.
[33] Dincer I, Ratlamwala TAH. Development of novel renewable energy based hydrogen production systems: a comparative study. Energy Convers Manag 2013;72:77–87.
[34] Rabbani M, Dincer I, Naterer GF. Experimental investigation of brine concentration and voltage effects on hydrogen production in an electrolysis chloralkali reactor. Chem Eng Process Process Intensif August 2014;82:9–18.
[35] Ameri M, Ahmadi P, Khanmohammadi S. Exergy analysis of a 420 MW combined cycle power plant. Int J Energy Res 2008;32(2):175–83.

Please cite this article in press as: Rabbani H, et al., A novel multigenerational hydrogen production system: Performance evaluation, International Journal of Hydrogen Energy (2017), http://dx.doi.org/10.1016/j.ijhydene.2017.02.068