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Exergetic and thermoeconomic analysis of a trigeneration system producing electricity, hot water, and fresh water driven by low-temperature geothermal sources

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ABSTRACT

Performance of a small-scale trigeneration system driven by low-temperature geothermal sources for producing fresh water, heating (hot water) and electricity is investigated from thermodynamic and economic standpoints. This system, utilizing a single stage absorption heat transformer leads to an increase in heat source temperature to be used in single stage evaporation desalination process and also providing water heating. Furthermore, an organic Rankine cycle is used for electric power generation. The developed model is validated with available data and effects of decision variables namely geothermal source, absorber and condenser temperatures on energy and exergy efficiencies of the overall system, power to water ratio and levelized cost of energy (LCOE) are investigated. The findings show that the increase in absorber and condenser temperatures leads to lower energy and exergy efficiencies, and higher LCOE and these effects are more significant at lower geothermal temperatures. Moreover, it is estimated that LCOE of proposed system is by far lower than that of a sole ORC powered with low geothermal water sources, whereas levelized cost of water (LCOW) is just comparable with small-scale membrane desalination processes. Utilizing a 100 °C geothermal water, the proposed system has a production capacity of 0.662 kg/s fresh water, 161.5 kW power, and 246 kW heat load.

1. Introduction

It has been reported that in the 20th century, the world population was tripled and water demand per capita doubled due to the improvement of standard lifestyle; therefore, a 6-fold increase in water withdrawals occurred [1]. This significant rise in consumption of water resources has caused more than 60% of the world population to have water shortage problems by the year 2025 [2]. On the other hand, it has been reported that between the years 2012 and 2040, there will be a 48% increase in energy consumption level in the world [3]. Hence, one of the major challenges our world faces in the coming years is supplying energy sources and freshwater. Cogeneration freshwater and electricity production systems, with the help of renewable energy sources, can play a crucial role in meeting this need and also decreasing environmental pollutions. In most of the previous studies, cogeneration freshwater and energy (electricity, heating or cooling) production systems powered by renewable energy sources have been investigated [4–9]. Sharaf et al. [4] introduced a cogeneration freshwater and electricity production system consisting of an Organic Rankine cycle (ORC) and the multi-effect distillation (MED) process. They analyzed their system in two different states from exergy and thermo-economic standpoints: in the first state, solar heat was only used in the MED process to produce freshwater. Whereas in the second, solar heat was first transferred to the ORC and then the output heat from the ORC was used in the MED process which led to simultaneous production of freshwater and electricity. Their findings suggest that both scenarios have almost similar results based on assessment parameters such as freshwater production cost, total solar field area and exergy destruction, whereas in the second state, electricity is also produced. Maraver et al. [5] investigated a multigeneration system for freshwater, electricity, heating and cooling production driven by biomass as the renewable energy source. The economic assessment results showed that the introduced system with biomass boilers has a high capital cost. Kouta et al. [6] analyzed the integration of two different supercritical CO2 Brayton cycles (SCO2), named regeneration and recompression SCO2 cycles, with multiple effect evaporation in a cogeneration water and electricity production

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Nomenclature

A	heat exchanger area (m^2)
ABS	absorber
AHT	absorption heat transformer
c	cost per exergy unit ($/GJ)
$\dot{C}$	cost flow rate ($/h)
CON	condenser
CRF	capital recovery factor
e	specific exergy (kJ/kg)
$\dot{E}x$	exergy flow rate (kW)
EVA	evaporator
Gen	generator
h	specific enthalpy (kJ/kg)
HEX	heat exchanger
i	interest rate (%)
LCOE	levelized cost of energy($/kW h)
LCOW	levelized cost of water($/$m^3$)
N	system life (year)
PWR	power to water ratio
$\dot{Q}$	heat transfer rate (kW)
s	specific entropy (kJ/kg k)
SSAHT	single stage absorption heat transformer
SEP	separator
T	temperature (K)
U	heat transfer coefficient (kW/m^2 °C)
$\dot{W}$	work (kW)
X	concentration
Z	investment cost of the system components ($)
$\dot{Z}$	investment cost rate of the system components ($/h)

Greek letters

φ	maintenance factor
η	efficiency
τ	number of system operating hours (h)

Subscript

abs	absorber
c	cold stream
con	condenser
ch	chemical
en	energy
eva	evaporator
ex	exergy
g	geothermal
h	hot stream
in	inlet
out	outlet
ph	thermo-physical
0	dead state

system. Their study showed that the recompression SCO2 cycle had a higher efficiency (approximately 6.25%) which led to more electricity generation. Demir and Dincer [7] thermodynamically evaluated an electricity and freshwater production comprised of a Brayton cycle with hybrid solar/natural gas system, a Rankine cycle, flash distillation and a thermo-electric generator. Their results indicated that energy and exergy efficiencies of this cogeneration system are 44.5 and 54.9%, respectively while 50% of the total input energy to the system is obtained from solar energy and the other 50% is obtained from natural gas. Calise et al. [8] investigated a multigeneration system comprised of an Organic Rankine cycle (ORC), an absorption chiller, and a MED which was powered by geothermal and solar energies. The results of the proposed system showed that total exergy efficiency in the thermal and cooling modes varied between 40–50% and 16–20% respectively. Recently, Azhar et al. [9] used double stage flashing and ocean thermal energy conversion (OTEC) systems in order to produce electricity, an absorption chiller and the MED process to produce cooling and freshwater. Moreover, heat of the exiting fluid from the turbine was utilized for industrial heating. The proposed multigeneration system was energetically and exergetically analyzed and total exergy and energy efficiencies reached 13.93% and 17.97%, respectively. Among the various types of renewable energies used in various multigeneration technologies, geothermal energy has unique features such as absence of variations for different seasonal and weather conditions [10]. In many regions of the world, there are geothermal sources at low temperatures (lower than 100 °C) along the coast and shallow depths of the sea which can be used economically in multigeneration systems. In addition, in contrast with common high temperature geothermal sources, the water produced from these low temperature sources is not toxic due to the low water depths [11,12]. Previous studies have shown that various electricity generation cycles such as Kalina and ORC which are fed by low temperature geothermal sources have efficiencies lower than 15% [13–15]. Therefore, multigeneration from a low temperature geothermal source can be reasonable and practical since it can improve total system efficiency. This is despite the fact that it is not possible to use these low temperature geothermal sources in a cost-effective fashion in common desalination processes such as multi-stage flash (MSF), membrane desalination (MD), and MED in small scales (lower than 100 m^3/day) due to the high energy consumption and high maintenance cost of these processes [16–18]. Bouguecha et al. [19] investigated the use of geothermal energy in a MD process. Their findings revealed that the cost of desalinated water reached 130 $/$m^3$ where 1 m^3/day fresh water was produced. In general, it was estimated that for small-scale desalination processes (< 100 m^3/day) powered by various renewable energies, the cost of fresh water for thermal and membrane processes reached up to 10 $/$m^3$ and 18.75 $/$m^3$, respectively [20,10]. Single stage processes can be considered as ideal options in small-scale water desalination, since these technologies have a small size, simple structure and low cost [7]. In the desalination process using a single stage evaporation unit, seawater evaporates by absorbing heat from a heat source and then as the vapor condenses in the condenser, freshwater can be obtained and the remaining brine returns to the sea. Absorption heat transformers (AHTs) are a suitable option to use low temperature sources in the single stage evaporation desalination process. An AHT is a device which causes an increase in temperature of low heat sources and consequently raises the temperature of low temperature sources to a suitable level. Normally, a single stage absorption heat transformer (SSAHT) delivers half of the absorbed heat to higher temperatures and the remaining heat enters the ambient at lower temperatures [21–23]. AHTs have been used extensively in water desalination and numerous studies have been conducted on the performance of integration of this system with single stage evaporation desalination process. Parham et al. [24] investigated the effects of various parameters on the performance of four different configurations of a SSAHT integrated with single stage evaporation desalination process. The thermodynamic analysis of their work showed that when the output heat from the condenser is re-used in the evaporator, the system works at the optimum state and the freshwater production reaches 0.2435 kg/s. Demesa et al. [25] used the sensible heat of the output brine from a single stage evaporation unit in order to preheat the fluid entering the evaporator of a SSAHT. This approach led to a 7.95 rise in performance coefficient of the SSAHT. Yari et al. [26] analyzed the utilization of 5