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Development, analysis and assessment of solar energy-based multigeneration system with thermoelectric generator

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ABSTRACT

This study presents comparative energy and exergy analyses of a solar energy based integrated multi-generation system with two unique configurations of thermoelectric generators. System 1 considers an integration of the output of thermoelectric generators with the parabolic solar collectors. In system 2, the thermoelectric generators are incorporated between solar heat exchanger and organic Rankine cycle 1. The heat rejected at low temperature interface of the thermoelectric devices generates electricity through organic Rankine cycle 2. The electricity generated by the thermoelectric generators is used to operate an electrolyzer to produce hydrogen. The utilization of thermoelectric devices developed in system 2 enhances the energy and exergy efficiencies of overall multi-generation system and organic Rankine cycle 1. In addition to this, the net amount of work output by organic Rankine cycle 1 is also improved greatly in system 2. The design configurations of the thermal system and the influences of the operating conditions on the energy and exergy efficiencies of multigeneration/overall system and organic Rankine cycle are investigated. The present results show that an increase in the mass flow rate of solar heat transferring fluid improves the work rate by the turbines and thermoelectric generators appreciably. The proposed system has superior and unique features as compared to the corresponding conventional systems based on thermoelectric generation.

1. Introduction

The natural sources of energy like sunlight, wind, geothermal, biomass, rain and tides are treated as renewable. These energy sources are replenished naturally after use. The energy from the sun is considered as renewable and sustainable. In addition to this, solar thermal systems can provide power indirectly. Solar concentrators like solar dishes, PTSC (parabolic trough solar collectors) and solar towers convert solar energy into advantageous outputs like heating, cooling and electrical power. Big power plants across the world are using PTSC (parabolic trough solar collector) since 1980s [1]. Therefore, in this study, PTSC technology is selected for heating the heat transfer fluid. Several multigeneration systems based on geothermal energy are developed and it is reported that the use of geothermal energy has been doubled since its discovery [2].

Multigeneration processes capabilities for high energy efficiencies, reduced operating expenditures and less pollutants [3]. The low efficiency of a single renewable energy based systems can technically be improved by integrating the solar and geothermal energy [4]. This kind of integration has resulted in more efficient systems as studied in the literature. Yuksel et al. [5] conducted the thermodynamic performance assessment of a novel environmentally-benign solar energy based integrated system and concluded that both energy and exergy efficiencies of the integrated system are increased when the temperature of the inner surface of absorber pipe is increased from 175 °C to 265 °C. Al Zareer et al. [6] developed a novel integrated system based on four-step copper chloride (Cu-Cl) cycle for water decomposition to produce electricity and hydrogen. Al-Sharafi et al. [7] considered economical aspects and environmental impact on the performance of hybrid power generation systems.

An integrated coal gasification multi-output system based on solar energy for the production of power, hydrogen, oxygen, heating, cooling and hot water was analyzed and assessed by Ozturk and Dincer [8]. In addition to this, significant increase in the energy and exergy efficiencies of single generation system is reported after shifting it to multigeneration [9]. Moreover, 10% increase in the exergy efficiency was also observed after the transformation of single-generation system to multigeneration system [9].

Solar energy is fundamental source of renewable energy among the other sources including; hydropower, waste heat, wind and biomass,

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Nomenclature

C	compressor
$\dot{E}x$	exergy rate (kW)
ex	specific exergy (kJ/kg)
h	specific enthalpy (kJ/kg)
K	thermal conductivity (W/m^2 K)
kW	kilowatt
kW h	kilowatt hour
kWe	kilowatt hour electric
kW ht	kilowatt hour thermal
L	length of semiconductor (m)
$\dot{m}$	mass flow rate (kg/s)
P	pressure (kPa)
$\dot{Q}$	heat rate (kW)
$\dot{S}_{gen}$	entropy generation (kJ/kg)
s	specific entropy (kJ/kg K)
T	temperature (K)
v	specific volume (m^3/kg)
$\dot{W}$	work rate (kW)
Z	figure of merit

Greek symbols

ρ	density (kg/m^3)
η	energy efficiency
ψ	exergy efficiency
Δ	difference

Subscripts

c	cold
cond	condenser
dest	destruction
en	energy
ele	electric
eva	evaporator
gen	generator
h	hot
HE	heat exchanger
cool	cooling effect of absorption chiller
hp	heat pump
n	semiconductor “n” type
P	pump
p	semiconductor “p” type
prod	product
t	turbine
TEG	thermoelectric generator
0	reference state (environment)
1, 2,….54	state number

Acronyms

COP	coefficient of performance
HCCI	homogeneous charge compression ignition
HEX	heat exchanger
HTF	heat transfer fluid (Therminol VP-1)
LCOE	levelized cost of electricity
LiBr-H_2O	solution of lithium bromide-water
multigen	multigeneration
O&M	operation and maintenance
ORC	organic Rankine cycle
PTSC	parabolic trough solar collector

etc. [10]. In addition to this, the ample availability of solar energy makes it less costly with zero pollution [11]. Moreover, useful output like power generation is possible through variety of solar heating systems which include; PTSC, solar dishes and solar tower.

In general, the multi-generation system uses one or more energy sources to produce diverse useful outputs. Multi-generation systems do not only mitigate environmental impact and cost but also increase efficiency and sustainability. There is a huge connection between the qualities of the available energy for multigeneration with the reference environment. Renewable energy based multigeneration systems produce better efficiency and these are sustainable [12]. Al-Sulaiman et al. [13] conducted a study on energy efficiency of electrical system and found that energy efficiency was increased to 94% in case of trigeneration. Ahmadi et al. [14] studied an ocean thermal energy conversion (OTEC) system for multigeneration thermodynamically and investigated the effects of operating conditions through parametric study. They used flat plate as well as PV/T solar collectors to produce fresh water through reverse osmosis (RO) plant, cooling through chiller and hydrogen through proton exchange membrane (PEM) based electrolyzer.

Ibrahim and Dincer [15] developed and evaluated experimental performance a solar energy based system, particularly for the production of cooling and potable water and recorded energy efficiency of 13.75% for the overall system. Islam et al. [16] developed an innovative cooling configuration of a solar energy-based multigeneration system and found an increase of 4.5% in energy efficiency and 5.1% increase in exergy efficiency of PV system. Solar and geothermal resources are combined by Bicer and Dincer [17] to produce hydrogen, electricity, heat and cooling.

Islam and Dincer [18] studied four embodiments of a cogeneration system. Moreover, an increase of 10% in exergy efficiency in the event of shifting system from single-generation to cogeneration was also reported in that study. Islam et al. [19] designed and investigated a solar energy-based multigeneration system for off-grid areas and compensated short fall in electricity through the combustion of hydrogen blended ethanol in homogeneous charged compression ignition (HCCI) engine. It is important to develop an advanced electrolyzer to fulfill the growing demand of hydrogen. The hydrogen production through electrolysis is practicable approach without the consumption of fossil fuels.

Thermoelectric generators carry huge potential to generate electricity through waste heat. Their low efficiency is dominated by other features like; design simplicity, easy to operate and zero emissions. These characteristics make them selective option for the generation of electricity. The effect corresponding to the location of thermoelectric device in refrigeration cycle was studied by Yilbas and Sahin [20]. It was observed that the coefficient of performance (COP) of combined system is enhanced by integrating thermoelectric device between ambient and condenser. Yilbas et al. [21] investigated that cold junction temperatures improve the performance of thermoelectric generators. Ali and Yilbas [22] modified the pin material configuration for increased efficiency and high power output. Power and efficiency of thermoelectric devices was optimized by Yazawa and Shakouri [23] through thermal contact. In thermoelectric devices, the asymmetrical legs increase the performance by harnessing the Thomson effect and increase the yield by lowering the thermal conductance of device [24]. A thermoelectric can produce electrical energy by harvesting waste heat at the exhaust of combustion gases [25]. The variation in efficiency and power produced by thermoelectric devices corresponding to the geometric configuration has been conducted in past [26,27].

In the open literature, the coupling of thermoelectric generators with multigeneration systems has been reported to some extent but up to the best knowledge of authors the investigation of the best