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Analysis and evaluation of a new renewable energy based integrated system for residential applications

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ABSTRACT

In this study, a solar based Rankine cycle and geothermal based system for multigeneration is designed and developed. It consists of a Rankine cycle with reheating for power generation, an absorption chiller cycle for cooling, a drying process to dry wet products, useful heat from the condenser of the Rankine cycle, and other useful heat out from heat exchangers. The overall energy and exergy efficiencies of the single generation and multigeneration systems are studied, and it is observed that the energy efficiency of the multigeneration system is higher than the single generation system. The energy efficiency of the single and multigeneration systems are 7% and 37%, respectively. Similarly, the overall exergy efficiencies for the single generation and multigeneration systems are also studied and presented in this paper. In addition to this, parametric studies are performed to observe the effects of different substantial parameters, namely inlet pressure and temperature of the turbine, and reference environment temperature in order to investigate the variations in the system performance in terms of the energy and exergy efficiencies.

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1. Introduction

The energy and environmental crises and challenges around the globe in the last few decades are a major concern to all countries. Natural resources such as wind, rain, tides, waves, sunlight, geothermal heat and biomass are considered to be excellent renewable energy resources. These can be restored naturally after use [1,2]. Vast portions of renewable electricity production are encouraged to address global warming issues and the growing insufficiency of hydrocarbon fuels [3]. Since it is both available and environmental friendly, solar energy is nowadays a widely used technology [4,5]. The solar energy is the most significant renewable-based replacement for fossil fuels; however, solar energy presents some challenges due to its fluctuating nature during day time as well as locations [6]. These kinds of fluctuations are an issue that requires potential solutions. Geothermal energy is also considered a reliable and environmental energy source which uses heat energy from the earth. There are a variety of applications for geothermal energy sources depending upon the amount of heat supplied to the plant, such as electricity production, space heating, water heating, cooling, agricultural drying, desalination, and industrial process heating [7]. One way to use geothermal energy more efficiently is by combining it with another renewable energy source such as solar energy. By combining two energy sources such as solar and geothermal, the deficiency of one source can be overcome by coupling with the other, which leads to a more efficient system. Another way to increase the efficiency of a system is by reducing the losses and using the waste heat to produce a useful commodity which leads to a cogeneration, trigeneration or multigeneration system [7].

In thermodynamic analyses of energy systems, exergy analysis, also called second law analysis, is a powerful tool. In other words, it is widely used in the design, simulation and performance evaluation of energy systems [4]. Dincer at el. [8] described the relationships between energy and exergy, exergy and the environment, energy and sustainable development, and energy policy in detail. The exergy analysis method is employed to detect and to evaluate quantitatively the causes of the thermodynamic imperfection of the process under consideration. Therefore, it can indicate the possibilities of thermodynamic improvement of the process under

Abbreviations: COP, coefficient of performance; EBE, energy balance equation; EES, engineering equation solver; EnBE, entropy balance equation; ExBE, exergy balance equation; HPT, high pressure turbine; HTF, heat transfer fluid; kW, kilowatt; kg, kilo gram; kPa, kilo pascal; kg/s, kilo gram per second; kJ, kilo joule; LPT, low pressure turbine; Li-Br, lithium-bromide; MBE, mass balance equation; MG, multigeneration; SG, single generation; TES, thermal energy storage; s, second.

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Nomenclature

$\dot{E}x$	Exergy rate (kW)
ex	Specific exergy (kJ/kg)
h	Specific enthalpy (kJ/kg)
$\dot{m}$	Mass flow rate (kg/s)
P	Pressure (kPa)
$\dot{Q}$	Heat rate (kW)
s	Specific entropy (kJ/kg K)
$\dot{W}$	Work rate (kW)
°C or K	Degree celsius or kelvin

Greek symbols

η	Energy efficiency
ψ	Exergy efficiency

Subscripts

A	Absorber
avg	Average
B	Boiler
C	Condenser
D	Destruction
E	Evaporator
en	Energy
ex	Exergy
FC	Flash chamber
G	Generator
geo	Geothermal
HE	Heat exchanger
in	Input
net	Net output
out	Output
P	Pump
prod	Product
RC	Rankine cycle
S	Source
T	Turbine
1, 2...46	State numbers
0	Ambient (or reference environment) condition

consideration. The concepts of exergy, available energy, and availability are fundamentally alike. The concepts of exergy destruction, exergy consumption, irreversibility, and lost work are also essentially similar. Exergy is a measure of the maximum useful work that can be done by a system interacting with an environment that is at a constant pressure P_0 and a temperature T_0 [9].

A multigeneration system is one which gives several outputs such as electricity, heating, cooling, and drying. Multigeneration utilises the waste heat of a power plant to improve overall thermal performance, basically consuming the "free" energy available via the waste energy [10]. A number of single and integrated systems have been analyzed by many researchers. Al-Sulaiman et al. [6] studied a multigeneration with trigeneration and showed that the maximum electrical energy efficiency was 14%, while with trigeneration alone the energy efficiency increased to 94%. Ahmadi et al. [11] developed a biomass based integrated multigeneration system in which he studied both the thermoeconomic and multi-objective optimization. In that system, he used exhaust gases from an organic rankine cycle (ORC) turbine for a heating process and a double-effect absorption chiller for a cooling effect. Ozturk et al. [12] proposed an integrated solar power tower and coal gasification system for multi-generation purposes. They conducted parametric studies to show the effects of environment temperature, compressor pressure ratio, nitrogen supply ratio for a combustion chamber and gas turbine inlet temperature on system performance. They also found the energy and exergy efficiencies to be 54% and 58%, respectively.

Coskun et al. [13] also examined mulitgeneration geothermal base systems and they found that the overall system energy and exergy efficiency increased by 3.40 and 1.12 times for the cooling season and about 4.25 and 1.25 times for the heating season, compared to the single power generating option. In another study, Al Zaharani et al. [14] also developed a multigeneration system by cascading a supercritical carbon dioxide (CO_2), Rankine cycle with Organic (R600) for power generation, hydrogen production and space heating. In their study, they found that the multigeneration system with geothermal energy has higher overall energy and exergy efficiency in the system. Ratlamwala et al. [15] proposed another geothermal base mulitgeneration system and found that increasing the geothermal source temperature, pressure and mass flow rate results in an increase in power and rate of hydrogen production. Lastly, Ozlu et al. [16] conducted a study of the exergy analysis of a solar thermal power system. They basically performed an energy and exergy analysis for the energy-based multigeneration system. Dincer at el. [17] confirmed that a multigeneration renewable energy base system offers better efficiency, cost, sustainability and environment. The literature suggests that multigeneration is advantageous to reduce greenhouse gas emissions and to help increase efficiency. This paper aims to develop, analyze and assess a new solar and geothermal energy based integrated system for multigeneration. In this regard, this study primarily consists of:

- Development, design and analysis of a solar and geothermal based system integrated system for multigeneration.
- Determination of energy and exergy efficiencies of all subunits, subsystems and the overall system for performance assessment and evaluation and possible improvements.
- Calculation of energy losses and exergy destructions of all major system components.
- Undertaking parametric studies to investigate the effects of varying various operating conditions and state properties on the system performance.

2. System description

The system primarily uses two renewable sources, i.e., solar and geothermal energies. The integrated system can be subdivided into three main cycles/sub-systems, namely: Rankine cycle, geothermal water cycle, and finally a vapour absorption cycle. Fig. 1 shows a schematic diagram of an integrated solar-geothermal system for multi-generation purposes. This multigeneration system comprises a solar system to raise the temperature of the heat transfer fluid (HTF), Rankine cycle with reheating to produce electricity, a geothermal source to run the turbine, an absorption chiller for cooling, and a heat exchanger to produce hot dry air for drying purposes.

2.1. Rankine cycle

Here, we use a solar energy system, which consists of two subsystems: the collector—receiver subsystem and the heat engine subsystem. The collector–receiver circuit consists of a number of parabolic collectors, organized in units that operate in tracking mode so that the working fluid goes through them. The heat engine circuit, which is basically a Rankine cycle, consists of a boiler, two-stage turbine (HPT and LPT or turbine 1 and 2), pump, and a condenser. The hot fluid enters the boiler heat exchanger at 600 °C (state 19) where it heats up the working fluid of the heat engine.

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