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Exergoeconomic and environmental analysis of a novel configuration of solar-biomass hybrid power generation system

Simin Anvari [a, *], Sharam Khalilarya [a], V. Zare [b]

[a] Mechanical Engineering Department, Technical Education Faculty, Urmia University, Urmia, West Azerbaijan, 57561-15311, Iran
[b] Faculty of Mechanical Engineering, Urmia University of Technology, Urmia, Iran

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ABSTRACT

In recent years, with increasing the industrial centers and indulgence in consumption of fossil fuels, the troublesome greenhouse gases such as carbon dioxide and depletion of fossil reservoir has become more prominent. One of the solutions to overcome this problem is utilization of renewable energy resources to generate power and electricity. Hence, a hybrid cycle consisted of biomass/solar is proposed in this paper. The proposed cycle is primarily postulated upon power production via the biomass energy where solar and steam turbine sections are incorporated to increase power output and decrease the CO_2 emission. First, the cycle undergoes through a comprehensive energy, exergy, exergoeconomic, and environmental analysis and the impact of produced power, production cost, and the amount of CO_2 emission of each mentioned sections on the overall produced power, the total cost, and the entire CO_2 emission of the hybrid cycle is discussed and evaluated. In the end, through a parametric assessment, the effect of important thermodynamic parameters on the overall cycle performance is studied. The results indicated that by adding the solar unit to biomass section, the power is increased by 30% and CO_2 emission has decreased by 22%. The capital cost of biomass and steam turbine units compared to the entire cycle are nearly equal as much as 15%, whereas for solar unit the amount of these costs compared to entire cycle is obtained as 71%.

1. Introduction

During the recent decades, fossil fuels have supplied majority of our power sources, since these were much more accessible and easier than energy from renewable energy reservoir, and up to recent years, the environmental challenges were of little significance. The CO_2 product that is known as the major constituent of the greenhouse gas plays a critical role in worldwide warming. Studies indicate that it is culpable of around two thirds of the greenhouse effect phenomena [1]. A significant share of the CO_2 discharged to the atmosphere is accredited to fossil fuel combustion. Resolving the environmental concerns that humanity encounters nowadays necessitates the long-run drastic measures for sustainable development. In this way, alternative energy sources seem to be one of the most influential and pragmatic solutions [2–4]. Renewable energy strategies present merchandisable energy by transforming natural incidents into useful forms of energy. The renewable energy advancements utilise the energy received from sun and its influence on the earth (would it be in the form of solar irradiance, wind, tidal, and energy in plants; i.e., biomass), gravity (tides), and the heat difference from crust to the earth's core as lava (geothermal) as the resources from which energy can be generated. Renewable energy systems may exhibit a useful interaction with the environmental, economic, and industrial affairs of the globe.

From long ago, the fossil fuels have been used in power plant systems for generation of diverse energy types (electrical, thermal, and cooling); while today the renewable energy sources can be replaced by fossil fuels in these systems. With design and installation of energy conversion systems driven with renewable energy sources, three chief targets (energy saving, generation of new working posts, and decrease in environmental pollution) can be accomplished [1]. According to performed studies, some of the researchers have used the solar energy as the source of renewable energy in thermodynamic systems and afterwards engaged with thermodynamic, exergoeconomic, or environmental analysis. Spelling et al. [5] carried out an exergoeconomic and optimization analysis of a combined power plant wherein a hybrid gas turbine with solar energy technology is used to develop a combined power plant. They used the solar energy to preheat the entering air into

* Corresponding author.
E-mail addresses: s.anvari@urmia.ac.ir, anvari.simin@yahoo.com (S. Anvari).

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Nomenclature

c	cost per unit of exergy ($/GJ)
CRF	capital recovery factor
CI	capital investment cost ($)
$\dot{E}$	exergy rate (kJ)
$\dot{E}_D$	exergy destruction rate (kW)
f	exergoeconomic factor
h	specific enthalpy (kJ/kg)
$\overline{h}_f^0$	enthalpy of formation (kJ/kg)
LHV	low heating value (kJ/kg)
HHV	high heating value (kJ/kg)
$\dot{m}$	mass flow rate (kg/s)
OMC	operating and maintenance cost ($)
P	pressure (bar)
PEC	Purchase equipment cost ($)
$\dot{Q}$	heat rate (kW)
r_{AC}	compressor pressure ratio
S	specific entropy (kJ/kg K)
T	temperature (K)
$\dot{W}$	power (kJ)
$\dot{Z}$	capital cost rate ($/h)

Greek Symbols

Δ	difference
η	efficiency
ε	exergy efficiency
φ_r	maintenance factor

Subscripts

AC	air compressor
CC	combustion chamber
Cond	condenser
D	destruction
e	exit condition
Eva	evaporator
Fuel	fuel
g	gas
hel	heliostat field
HP_GT	high pressure gas turbine
i	inlet condition
IHE	intermediate heat exchanger
k	component
LP_GT	low pressure gas turbine
P	Pump
PP	pinch point
rec	receiver
T	steam turbine
k	component
L	Loss
tot	Total
0	dead state

combustion chamber. This process led to a significant reduction in the fuel consumption. The results indicated that the solar gas turbine technology is considered as a promising technology as an alternative. Moreover, the cycle analysis results showed that the developed solar combined cycle of power plant has a 60% reduction in electrical costs compared to parabolic power plants, additionally a 32% reduction was observed in CO_2 emission compared to combined power plants with parabolic collectors. Livshits and Kribus [6] considered the performance of a steam injection gas turbine (STIG) cycle with and without usage of solar energy. The obtained results showed that with hybridization of thermal solar energy into STIG cycle, the efficiency of cycle increases about 40%–55%, while before hybridization the STIG cycle had the efficiency of around 25%–35%. Selwynraj et al. [7] examined the annular performance of the proposed cycle in Ref. [6] with the obtained data from the climactic condition of India. They reported that the annular emission of CO_2 is analogous to the combined cycle power plants and is less than that of gas turbine technologies. Amiri et al. [8] utilized the technology of solar thermal energy integration with the gas turbine in cogeneration power plant (CCHP). Their results accentuated that the use of solar thermal energy in preheating of the inlet air into combustion chamber would increase the fuel efficiency from 31% to 85%. This action also led in 400 kg reduction of CO_2 amount, i.e. from 680 kg/MWhe to 270 kg/MWhe. Korzvnietz et al. [9] designed, manufactured, and exploited a hybrid Brayton/solar power plant. They were able to achieve 800 °C and above temperatures by help of solar heliostat receivers and thus would cause an increase in the cycle performance.

However, some of the researchers tapped the biomass renewable energy in the thermodynamic cycles; therein Ahmadi et al. [10] practiced an exhaustive analysis of a multi-generation power plant driven by biomass base. The produced heat from the combustion of biomass is applied as the input of the Rankine cycle and in the following, the waste heat of Rankine cycle is used to run other components of the cycle. Their results indicated that the proposed system based on biomass gives comparatively lower CO_2 emission than that of conventional power generation and cogeneration systems. Khanmohammadi et al. [11] developed a thermodynamic and economic model for a combined Rankine cycle and external combustion gas turbine with gasification of biomass. Next, the multi-objective optimization is done through heuristic algorithms to find the optimum design parameters. The sensitivity analysis of the cycle in design points showed that the reduction of gasification temperature leaves a positive impact on the efficiency and thereby can consistently increase the system costs. Athari et al. [12] studied a gas turbine power cycle exergoeconomically on the basis of biomass gasification with and without fogging inlet cooling. The results imply that the difference between relative cost and exergoeconomic exergy factor for the proposed cycle is more than the power generation cycle driven with natural gas fuel. Baghernezhad et al. [13] compared the use of different renewable energy sources in a cogeneration cycle economic wise, where fuel cell, biomass, and solar as renewable energy sources were applied in this regard. They reported that the exergy efficiency of a triple cogeneration cycle with application of fuel cell is more than other cases (about 64%), in other hand, the exergy cost unit is the highest in this case and the triple cogeneration cycle with application of biomass gives the lowest cost. In some of the conducted studies, it is observed that the solar energy is adopted for biomass combustion. Bai et al. [14] surveyed the cogeneration cycle in thermodynamic and economic terms for production of methanol and power on the base of biomass combustion through the solar energy. Their work was such that the concentrated solar thermal energy was used within 1000 K- 1500 K temperatures for biomass combustion. Thereafter, the synthesized gas from biomass gasification was employed for methanol production by the use of synthesized reactor. Liu et al. [15] investigated thermodynamic performance of a hybridized solar/biomass cogeneration cycle in two modes. In the