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Proposal and analysis of two novel integrated configurations for hybrid solar-biomass power generation systems: Thermodynamic and economic evaluation

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ABSTRACT

Hybridization of solar and biomass energies, as two types of renewables, represents a resourceful way of complementing each other to overcome their individual drawbacks. In the present work, two novel solar-biomass hybrid power generation systems are proposed, modeled and compared with each other as well as with the standard biomass-based system without solar energy. In both the proposed systems biomass is first gasified in a gasifier and then syngas is used in a gas turbine plant combined with a Rankine cycle. In proposed systems the solar energy is used in the bottoming Rankine cycle, where the first system employs it in an indirect way to heat the feed water before deaerator while the second system adopts the solar energy in direct steam generation mode to generate additional steam for low pressure steam turbine. Thermodynamic and economic models are developed to investigate the systems' performances from the viewpoints of energy, exergy, economic and environmental. According to the results of economic evaluation, the levelized cost of electricity for standard, the first and second proposed configurations are obtained 79.34, 79.88 and 74.94 $/MWh, respectively. Also, the values of 0.79, 0.77 and 0.62 t/MWh are calculated for CO_2 emission for standard, the first and second proposed configurations, respectively.

1. Introduction

The primary energy source that is being used in the world today is the fossil one from which many of the environmental problems, including climate change and air pollution, results. The substantial availability of renewable energy sources in the form of solar, biomass, hydropower and wind energy offers opportunities of sustainable energy-based development. Solar energy is the most available resource of renewable energy. Based on Renewables Global Status Report [1], total global renewable power capacity is reached to nearly 2017 GW at the end of 2016. The electricity generation capacity by renewable resources at the end of 2016 are reported as; geothermal: 13.5, bio: 112, hydropower: 1096, solar: 307.8 and wind: 487, all in GW [1].

Among the renewable resources solar and biomass energies are of major importance for some advantages such as abundance and helping in reduction of global warming [2]. Biomass is a biological material which is produced during the photosynthesis of water, carbon dioxide and solar energy [3]. Biomass generally consists of agricultural, forest and paper waste and since it is being generated continuously, it is commonly considered as a renewable energy resource [4]. The gasification process is the most common technology used for turning biomass into a biofuel, which is referred to as syngas (a mixture of hydrogen, carbon monoxide, carbon dioxide, water vapor and methane), that is being employed for power generation purposes [5]. Although the efficiency of these systems is rather low, but due to the environmental advantages they are much preferred to fossil fuel plants [6]. However, regarding the biomass plants some aspects have to be noticed. Unlike the fossil fuels, biomass is not available in one place in a concentrated form, so it could be collected and transported anywhere which is required. Biomass availability at a reasonable price over the plant lifespan is an essential factor for a biomass project. Biomass is a dispersed fuel with low-energy density and its transportation commonly is more expensive than oil, gas, or coal. Thus, the biomass should be collected regionally and its local availability is a critical issue. However, the locally available biomass allows the widespread production of energy at reasonable costs and can help to mitigate climate change, develop rural economies and increase energy security [7].

Solar energy can be converted into electricity power using both direct and indirect technologies. Solar thermal electricity generated by Concentrating Solar Power (CSP) plants is one of those technologies

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Nomenclature

CETD	cold end temperature difference
CSP	concentrating solar power
CRF	capital recovery factor
DNI	direct normal irradiance
DSG	direct steam generation
$\dot{E}_D$	exergy destruction
G	Gibbs function
$\bar{h}_f^0$	enthalpy of formation
i_r	interest rate
HPT	high pressure turbine
HRSG	heat recovery steam generator
HTF	heat transfer fluid
HX	heat exchanger
ISGCC	integrated solar gasification combined cycle
K	equilibrium constant
LCOE	levelized cost of electricity
LHV	lower heating value
LMTD	logarithmic mean temperature difference
LPT	low pressure turbine
$\dot{m}$	mass flow rate
n	number of plant operation (year)
OFWH	open feed water heater
PG	power generation
R_p	compressor pressure ratio
$\dot{W}$	power
R-SRC	regenerative steam Rankine cycle
X_j	kilomoles of component
Z	investment cost of system

Subscripts

0	dead state
AP	air preheater
C	compressor
CC	combustion chamber
CON	condenser
g	gasification
G	gasifier
GT	gas turbine
i	input
rec	receiver
SF	solar field
ST	steam turbine

Greek letters

η_c	collector efficiency
$\eta_{is,C}$	compressor isentropic efficiency
$\eta_{is,GT}$	gas turbine isentropic efficiency
$\eta_{is,sT}$	steam turbine isentropic efficiency
$\eta_{is,P}$	pumps isentropic efficiency
η_I	energy efficiency
η_{II}	exergy efficiency
ε_{em}	emission

which has experienced significant growth in recent years [8]. In CSP plants different types of solar collectors including linear Fresnel, parabolic through, parabolic dish and heliostats are employed for heat generation at different temperatures [9]. The main challenge in these types of power plants is the low efficiency and inconsistency in power generation. In order to reduce the expenses and increase the efficiency of these systems, they are often combined with other renewable resources such as biomass.

Hybridization of solar and biomass energy combines two energy sources that complement each other, both seasonally and diurnally, to overcome their individual drawbacks [10]. Such a combination and hybridization of energy sources may results in a higher energy conversion efficiency [11]. In these systems biomass can be used through direct combustion to provide the required thermal energy to drive a power generation system [12]. Also, it can be used via the gasification process to produce the syngas as the heat source for simple or combined cycles [13]. In many published papers in this area, regarding endothermic gasification process solar energy is used as a heat source for implementing biomass thermochemical reactions. These systems are known as Integrated Solar Gasification Combined Cycle (ISGCC) [14]. Hybridization of biomass with solar energy of different configurations in the context of their suitability in Europe are discussed by Hussain et al. [15] and technologies, climate data and economic performance of these systems are studied to identify the key drivers of system selection for designing large scale solar-biomass hybrid power plants. Liu et al. [16] proposed and analyzed two solar-biomass hybrid combined cycle systems, the first one uses solar energy for biomass gasification and the second one uses solar energy directly for heating the compressed air. Their results showed that the first system has better performance reaching to a solar-to-electricity efficiency of 18.4%. A new solar-biomass power generation system that integrates a two-stage gasifier is proposed by Bai et al. [17] in which solar thermal energy with different temperature levels for driving the biomass pyrolysis (about 643 K) and gasification (about 1150 K) is provided with two types of solar collectors. They concluded that, under the nominal condition for their proposed system, the overall energy efficiency reaches to 27.93%. A low temperature steam gasification process is modeled numerically by Ravaghi et al. [18] in which the required steam is produced by concentrated solar power system. According to the results, their proposed system is much more efficient as compared to the gasification process with high temperature. A biomass high temperature steam gasifier assisted with solar energy and integrated with a micro gas turbine with an output of 20 kWe is proposed by Campo et al. [19] who investigated the effects of some important operating parameters on the system performance.

In some other studies combining the biomass and solar systems, solar energy is used to assist the steam generation process in Heat Recovery Steam Generator (HRSG). Tanaka et al. [20] investigated a hybrid solar-biomass power generation system in which the heat generated by CSP process is used to assist the steam generation in HRSG to run the bottoming Rankine cycle and to be used as the gasification agent. They indicated that, the increase in thermal input from CSP has positive effect on overall performance of the hybrid system until this thermal input becomes dominant against thermal stream related to the gasifier and the gas turbine. Milani et al. [21] proposed three hybrid solar-biomass power plant concepts for a combined Brayton-Rankine cycle including: (1) series design, (2) parallel design and (3) steam extraction design. Their results indicate that, the series design holds the highest levelized cost, the parallel design has the highest installed capacity and the steam extraction design is placed between the other two proposed systems regarding the capacity factor and the annual power generation. A hybrid solar-biomass system, relies on a combination of parabolic trough solar collectors and biomass burning boiler to drive an Organic Rankine Cycle (ORC), is proposed and modeled by Soares and Oliveira [22]. They concluded that the system annual electricity yield is significantly improved by hybridization increasing from 3.4 to 9.6%. Pantaleo et al. [23] investigated the performance of a hybrid solar-biomass combined cycle composed of a 1.3 MWe externally fired gas-turbine and a bottoming ORC plant and reveled higher global energy conversion efficiencies with using CSP integration.