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Thermodynamic evaluation of a novel solar-biomass hybrid power generation system

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ABSTRACT

A solar-biomass hybrid power generation system, which integrates a solar thermal energy collection subsystem, a biomass steam boiler and a steam turbine power generation block, is developed for efficiently utilizing renewable energies. The solar thermal energy is concentrated by parabolic trough collectors and is used to heat the feed-water to the superheated steam of 371 °C, then the generated solar steam is further heated to a higher temperature level of 540 °C via a second-stage heating process in a biomass boiler, the system power generation capacity is about 50 MW. The hybrid process of the solar energy and biomass contributes to ameliorating the system thermodynamic performances and reducing of the exergy loss within the steam generation process. The off-design evaluation results indicate that the annual net solar-to-electric efficiency of the hybrid power system is improved to 18.13%, which is higher than that of the typical parabolic trough solar power system as 15.79%. The levelized cost of energy drops to 0.077 $/(kW h) from 0.192 $/(kW h). The annual biomass consumption rate is reduced by 22.53% in comparison with typical biomass power systems. The research findings provide a promising approach for the efficient utilization of the abundant renewable energies resources and the reduction of carbon dioxide emission.

1. Introduction

Owing to the distinct advantages, e.g., clean, sustainability, etc., solar energy and biomass are regarded to be promising renewable energies and will contribute to the alleviation of the current energy supply and environment concerns [1]. Currently, the Concentrated Solar Power (CSP) technology is one of approaches of utilizing the abundant solar energy, some solar power plants have achieved the commercial operation [2].

The intermittent nature of the solar energy leads to unfavorable solar power system performances and low capacity factor. Furthermore, the integration of the efficient heat storage systems (molten salts, concrete and latent heat) will results in a higher specific investment of the solar power plant. Biomass is another type of renewable energy resource from forestry and agricultural wastes, moreover, the biomass combustion is a mature renewable power generation technology [3]. Whereas, the seasonal variability and the limitation of the collection radius bring a challenge of the consistent and sufficient fuel supply, the plant scale has to be restricted and also leads to a low energy conversion efficiency.

Solar energy and biomass, with different properties, provide an opportunity to realize the hybrid utilization to compensate their individual drawbacks. Apart from enhancing the energy conversion process, the hybrid biomass can be used as a complementary fuel to achieve a constant and longer operating duration for a solar energy system. As compared with the biomass-only system, the required biomass consumption in the hybrid power system will be reduced because of the introduction of the solar energy, thereafter, the risk associated with the biomass supply can be decreased.

At present, various hybrid routines are available and numerous solar-biomass hybrid utilization systems have been developed, in which the solar thermochemical reaction of driving the biomass gasification is one of the effective hybrid methods [4]. Bai et al. [5] proposed and evaluated a solar-biomass gasification system for producing the methanol and electricity. Zeng et al. [6] experimentally tested the performances of solar driven biomass pyrolysis. Meanwhile, the solar thermal energy can be hybrid utilized through participating the biomass gasification process by provid-

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Nomenclature

A	energy level
C	capital cost
CRF	capital recovery factor
DNI	direct nominal irradiation
e	exergy
f	biomass feed rate
F	annual biomass consumption rate
H	enthalpy
i	bank rate
LCOE	levelized cost of energy
n	system lifetime
P	generated power
r	ratio
R	radius
S	solar collection area
t	time
T	temperature

Greek letters

η	efficiency
β	quality factor

Subscript

bio	biomass
ch	chemical
col	collection
EPC	engineering procurement construction
HTF	heat transfer fluid
ins	insurance
O&M	operation & maintenance
pb	power block
ph	physical
sol	solar
sol-elec	solar-to-electric
sys	system
TES	thermal energy storage

ing the solar-steam [7]. Similarly, Liao et al. [8] experimentally studied a supercritical water biomass gasification method using the concentrated solar energy, the hydrogen content in the produced syngas was higher than 40%. Besides, diverse solar-biomass hybrid systems for CCHP production (e.g. combined cooling heating and power) [9] was thermodynamically evaluated. Soares et al. [10] developed a system that combines the concentrating solar energy and biomass sources to drive an Organic Rankine Cycle, the system annual yield is significantly increased to 9.6% from 3.4%. Prasartkaew et al. [11] experimentally investigated a solar air-conditioning system with the biomass as the backup fuel and realized the satisfactory performances.

The concentrated solar power is one of major approaches for the utilization of the solar energy, various hybrid routines of the CSP-biomass were therefore developed. Yasuto et al. [12] proposed a hybrid concept by injecting the solar energy into the HRSG in a biomass gasification combined cycle system. Liu et al. [13] investigated two solar-biomass hybrid combined cycle power generation systems, the hybrid technical modes of solar driving biomass gasification and the solar energy heating the compressed air were compared. In addition, Hou et al. [14] developed a system to integrate the solar energy into a typical biomass power generation system, the solar energy was used to replace the extraction steam for preheating the feed water, thus the previous extraction steam can be saved and continuously flows into the turbine's lower stages for the power generation. Suojanen et al. [15] modeled and analyzed three hybrid configurations for the linear Fresnel collector solar field with direct steam generation and conventional steam power plants, the emission can be reduced by 20%.

Meanwhile, the solar parabolic collectors and biomass combustion can be arranged in parallel to produce steam for the power generation, constant and longer system operation can be realized [16]. Peterseim et al. [17,18] investigated the technical routines of using biomass materials to externally superheat steam in conventional parabolic trough plants, different CSP-biomass hybrid configurations were also developed and evaluated, the results indicate that the net efficiency of the solar-to-electricity can be improved with the decrease of the specific investment. Soria et al. [19] proposed a hybrid solar-biomass strategy for developing the concentrated solar power according to the renewable energies situation of Brazil. In addition, Hussain et al. [20] assessed various types solar-biomass hybrid routines in Europe. Nixon et al. [21] analyzed the technical feasibility of developing the hybrid solar-biomass power system in India.

Nevertheless, these published works emphasized the development of the concept and the system modeling for the solar-biomass hybrid utilization. However, the respects, such as the hybrid mechanism, the off-design performances and the hybrid operation characters of the existing solar-biomass hybrid systems, need to be deeply investigated. Therefore, in this paper, a solar-biomass hybrid power system with two-stage steam heating routine is proposed, the hybrid mechanisms and the system off-design performances are evaluated.

The rest of this paper is organized as follows. In Section 2, a solar-biomass hybrid power generation system is developed and the system configuration is described. In Section 3, the system thermodynamic evaluation method is described. The results and discussion on the system thermodynamic and the economic analysis are presented in Section 4. Finally, main conclusions are summarized in Section 5.

2. Solar-biomass hybrid power system

Currently, a large portion of commercial CSP plants choose the parabolic trough collector technology. However, due to the physical properties of the synthetic oil as a Heat Transfer Fluid (HTF) and the coating material properties of the receiver, the system operation temperature is limited. Therefore, it is challenging to improve the thermodynamic performances in a CSP system. In order to compensate the aforementioned issues, a solar-biomass hybrid utilization concept and a hybrid power generation system are developed.

2.1. Hybrid concept

Based on the solar collection characters in a parabolic trough collector for the power generation, the hybrid utilization with the biomass combustion process is a promising option. The concept diagram of the solar-biomass hybrid utilization and the T-S diagram within the hybrid utilization process are depicted in Figs. 1 and 2, respectively.

The solar irradiation can be normally used to generate the superheated steam with the temperature of 371 °C as a typical