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Thermodynamic and economic evaluation of a solar aided sugarcane bagasse cogeneration power plant

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A B S T R A C T

This work evaluated the integration of Concentrated Solar Power (CSP) with a sugarcane bagasse cogeneration plant located in Campo Grande (Brazil). The plant is equipped with two 170 t/h capacity steam generators that provide steam at 67 bar/525 °C. Superheated steam is expanded in a backpressure and in a condensing-extraction turbine. The evaluated hybridization layouts were: (layout 1) solar feedwater pre-heating; (layout 2) saturated steam generation with solar energy and post superheating in biomass steam generators and (layout 3) superheated steam generation in parallel with biomass boilers. Linear Fresnel and parabolic trough were implemented in layouts 1 and 2, while solar tower in layout 3. The exportation of electricity to the grid was increased between 1.3% (layout 1/linear Fresnel) and 19.8% (layout 3) in comparison with base case. The levelized cost of additional electricity was accounted between 220 US$/MWh (layout 3) and 628 US$/MWh (layout 1/linear Fresnel). The key factor related to layout 3 was the improvement of solar field capacity factor due to the solar-only operation of this approach. These aspects demonstrate that the combination of solar and bagasse resources might be the key to turn CSP economically feasible in Brazil.

1. Introduction

Solar and biomass are both renewable energy resources which contribute to the electricity generation at low CO_2 emission levels. One important problem related to the biomass power plants operation, however, consists on the availability of fuel along the year. This is also true for the sugarcane bagasse power plants in Brazil that are operated mainly during the sugarcane harvest period [1,2]. In this regard, the Concentrated Solar Power (CSP) hybridization of biomass plants has been studied under different configurations [3–6]. The central idea consists on displacing fuel consumption during sunny hours and providing power supply on a biomass only mode during hours of no solar irradiation incidence – the so-called fuel economy hybridization mode. Solar heat load can also be used to provide power boosting during sunny hours – the so-called power boosting hybridization mode. These approaches can be applied to new plants and also to existing ones. Sharing common infrastructure turns possible the reduction of solar energy implementation costs.

Distinct integration layouts of CSP and conventional plants based on Rankine steam cycles are possible. The most explored scheme in literature is the solar aided feedwater heating concept (SAFWH) which can be performed by the displacement of bleed-off steam extractions of the regenerative feedwater heating system by solar heat load. Several works demonstrated that the higher the steam parameters of bleed-off steam extraction displaced, the higher is the efficiency in converting solar heat into electricity or in terms of fuel economy [7–10]. Furthermore, solar-to-electricity efficiency levels greater than for solar-only power plants operating under the same solar field heat transfer fluid average temperature can be achieved as the exergy destruction inherent to the conventional feedwater heating process is avoided [11,12]. As drawbacks of the SAFWH approach, nevertheless, it can be mentioned that: (i) the annual solar share is generally reduced [6,13,14] and (ii) the solar-only operation is not possible once steam generation is performed in the conventional boiler.

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Power plants can also be hybridized by considering the integration of CSP in parallel with conventional steam generators based on coal, natural gas or biomass combustion. It is turned possible, thereby, to increase the solar share of hybridization. Peterseim et al. [3] and Nixon et al. [15] evaluated the operation of conventional steam generators in parallel with CSP where both systems were able to produce superheated steam with the same temperature and pressure parameters. This approach was implemented commercially in the 22.5 MW capacity Borges power plant where the solar field and biomass steam generator systems were designed to provide the annual solar share of around 50% under the local weather conditions of Lleida in Spain. Finally, the hybridization of CSP and systems based on coal or biomass combustion was also evaluated in order to increase the temperature of steam after its generation in the solar field. As examples, Peterseim et al. [4] evaluated the post superheating of steam produced with a parabolic trough solar field with a biomass fired superheating system, while Zhao [16] proposed the production of saturated steam to displace the load of a coal fired steam generator. Produced saturated steam in solar field was then injected into the conventional steam generator drum for post superheating.

The installed capacity of sugarcane bagasse power plants in Brazil reached 10.6 GW in the first quarter of 2016 – representing 7.1% of the Brazilian electricity installed capacity [17]. Traditionally the bagasse power plants are cogeneration unities directly located in the sugarcane factories in order to deliver the on-site electricity and heat demands. This explains the large total amount of 410 bagasse fueled unities under operation today in Brazil [17]. In the last decades, due to a relevant increase in the Brazilian electricity demand and also due to the Brazilian electricity sector decentralization in 2000, the focus has changed from fulfilling the on-site sugarcane factories demand to exporting electricity to the grid. Considering the period 2005–2013, the electricity exportation was raised each year by 34% on average, so that in 2013 a total amount of 15,067 GWh was produced by bagasse fueled power plants [18]. The potential for improvements in terms of electricity exportation to the national grid by the sugarcane sector is yet significant once it is estimated that it could reach 193,596 GWh until the year 2022 [18].

The operation of the sugarcane bagasse power plants occurs mainly during the sugarcane harvest that extends from April to December in the center-south region of Brazil [1,2]. In the rest of the year, most plants remain out of operation and no electricity is produced. Therefore, the concept related to the hybridization of cogeneration plants of sugarcane sector with CSP was presented in Ref. [19]. In that preliminary work, the authors evaluated the SAFWH integration layout with parabolic trough collectors under thermodynamic and economic aspects. The main idea consisted on providing the solar integration in a fuel economy mode during harvest to economize bagasse to be then used to operate the power plant during off-season. It was identified, nevertheless, that the proposed hybridization layout was expensive in terms of electricity generating costs and further hybrid configurations and CSP technologies could be tested in order to find more feasible alternatives.

In this regard, the aim of this work consisted on extending the cogeneration power plants hybridization concept presented in Ref. [19] through the comparison of three distinct integration layouts, namely: (layout 1) solar feedwater pre-heating; (layout 2) saturated steam generation with solar energy and post superheating in biomass steam generators and (layout 3) generation of superheated steam in parallel with biomass steam generators. Three CSP technologies were also considered according to the steam cycle injection point temperature requirement of each hybridization scenario. The linear Fresnel and parabolic trough collectors were implemented for integration layouts 1 and 2, while solar tower with direct steam generation was implemented in layout 3. The scope was here limited to the retrofit of a conventional cogeneration plant aiming minimal modifications on original installations.

2. Method

2.1. The solar aided cogeneration plant concept

Bagasse is the fibrous residue which remains after the sugarcane juice extraction process. The bagasse consists of cellulose, hemicellulose and lignin. Due to the on-site electricity and heat demand of sugarcane processing factories, the bagasse is directly used as fuel in cogeneration power plants. The hybrid operation of a cogeneration power plant in a fuel economy mode during the harvest period is here proposed and evaluated under different layouts. The stored bagasse can be then used to run the power plant during off-season. This concept is shown in Fig. 1.

Whereas sugarcane cannot be stored, the operating time of the process factory is coupled to the sugarcane harvesting period, which typically ranges in the center-south region of Brazil from April to December. Outside this period, most of the cogeneration power plants are out of operation and no electricity is exported to the grid. In contrast to sugarcane, bagasse is storable. Hence, by replacing partially bagasse with solar energy during normal operating season, the overall power plant operating period can be extended to off-season through the use of the stored bagasse.

2.2. Tested hybridization layouts

The ways of concentrating solar energy can be divided into linear and point focusing technologies. Parabolic trough and linear Fresnel collectors belong to the linear focusing technologies, whereas the main point focusing technologies are the central receiver (solar tower) and the parabolic reflectors (Dish). Considering the market availability and the current state of development, the following technology options were chosen for the present case study: Linear Fresnel (LF); Parabolic Trough (PT) and Solar Tower (ST). An overview for the three named CSP options is presented in Table 1.

In this work the analysis was limited to the technology options

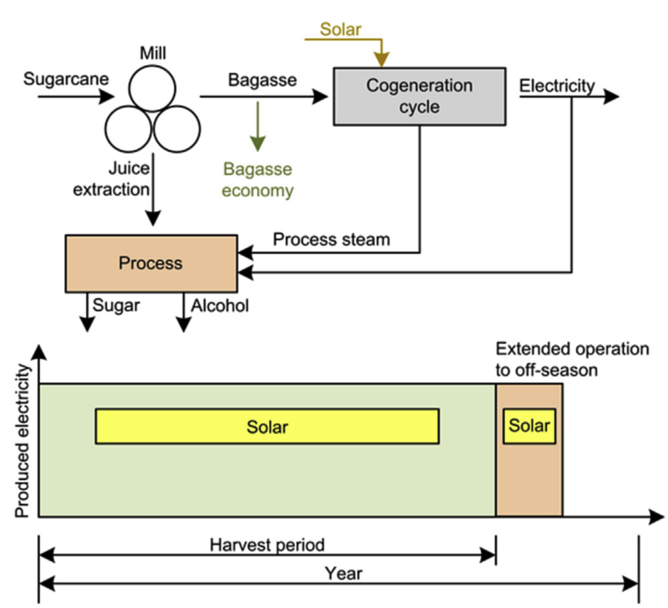

Fig. 1. Schematic of process and illustration of the solar aided cogeneration plant concept.