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Hybridization of concentrated solar power with biomass gasification in Brazil's semiarid region

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A B S T R A C T

This study aims to propose and analyze different options for hybridizing Concentrated Solar Power (CSP) with biomass, through gasification for power generation. A hybrid CSP-biomass power plant through gasification is an innovative concept which allows the integration of combined cycle for power generation, sun-biomass hybridization and syngas storage. Therefore, this study addressed the proposition of the hybridization concept and the simulation of benchmark power plants for a suitable Brazilian site (high direct normal irradiation and low-cost biomass availability). Three power plant concepts are proposed and simulated in Aspentech Hysys and System Advisor Model (SAM): (i) Series design; (ii) Parallel design, and (iii) Steam Extraction design. For the same gasifier, the Series design holds the highest levelized cost, while the Parallel design presents the highest installed capacity, but the lowest capacity factor. Finally, the Steam Extraction design is placed between the other two proposed plants regarding the capacity factor and the annual energy generation.

1. Introduction

Concentrated solar power can play a key role in the transition towards a green economy [1]. It is also seen as one of the critical technologies for a sustainable development in Brazil [2]. CSP allows thermal energy storage and hybridization with other thermal energy sources (e.g. biomass, natural gas, etc). These possibilities enhance the power plant's dispatchability and firm energy generation. Thus, CSP is more suitable to deal with the intermittency of natural resources than other variable renewable energy technologies (VRE) (wind and photovoltaic).

CSP technology uses direct normal irradiation (DNI) as primary energy source [3,4]. Brazil has the advantage of presenting a high DNI range (above 2000 kWh/m^2/year) in a large semiarid region (see Fig. 1) where local biomass is available [5]. Thus, it is worth evaluating the possibilities of hybridizing biomass and solar energy, especially in Brazil. Studies such as [6–8], showed that Bom Jesus da Lapa (BJL) is a proper site in Brazilian semiarid region for a CSP power plant. Nevertheless, Brazil has several other places which are suitable for CSP power plants as described by [8,9]. In the next paragraph, the studies that assessed the possibilities of hybridization between CSP and biomass will be presented. It is important to say that some of them assumed that biomass is available, and, hence, did not focus on a specific location in their case studies. However, biomass logistic is indicated to be one of the hurdles for these kind of power plants [10]. Therefore, although the main contribution of this paper is the simulation of virtual designs of hybridized CSP-biomass gasification, the study tried also to use real data from a country where biomass is available close to suitable sites for CSP.

So far, some scientific studies assessed the possibilities of hybridization between CSP and biomass. Some, focused on the well-known processes of direct biomass or biogas combustion as heat source for a simple (Rankine or Brayton) and combined cycle [12–17]. For Brazil, Soria et al. [5], evaluated the possibility of hybridization of biomass direct combustion and the parabolic trough technology, focusing on a conventional Rankine cycle. Other studies proposed the coupling of CSP and biomass gasification, but focused on the gasification process itself, and did not propose a power generation cycle [18–21]. Hybridizing these two technologies for production of biofuels, using solar energy to generate steam, used as a gasifier agent is assessed in other studies. So far (at least

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Nomenclature

A_{tp}	parallel cycle stored syngas in one year	M_t	operation and maintenance costs per year
A_f	syngas to be stored in order to deal with fluctuations in one year	n	system lifespam
BFB	Bubbling Fluidized Bed	O&M	operation and maintenance
BJL	Bom Jesus da Lapa	Q_a	total annual heat stored as syngas
BUS	Backup System	Q_e	heat requirement to bring the water form standard conditions to gasifier inlet conditions
CAPEX	Capital Expenditure	Q_f	thermal power to deal with renewable resource fluctuation per hour
CC	Gas Turbine Combustion Chamber	Q_{hysys}	thermal power requested by the process modelling per hour
CEST	Condensing-Extraction Steam Turbine	Q_i	hourly heat generated by the CSP facility
CF	Capacity Factor	r	discount rate
CFB	Circulating Fluidized Bed	SAM	System Advisor Model
CSP	Concentrated Solar Power	ST	steam turbine
DNI	Direct Normal Irradiation	TES	Thermal Energy Storage
DOE	U.S. Department of Energy	VRE	Variable Renewable Energy
DSG	Direct Steam Generation	$t_{w/-}$	hours per year with solar resource
E_t	electricity per year	t_s	hours per year without solar resource
F_t	fuel cost per year	α_e	syngas flow to storage in the Steam Extraction Cycle
GT	Gas Turbine	α_t	total syngas flow produced by the gasifier
HTF	Heat Transfer Fluid	α_{cc}	syngas flow to CC
HRSG	Heat Recover Steam Generator	α_{np}	parallel cycle Syngas flow to GT in the hours without solar resource
IECM	Integrated Environmental Control Model	β	steam flow required by the gasifier
IGCC	Integrated Gasification Combined Cycle		
ISGCC	Integrated Solar Gasification Combined Cycle		
I_t	CAPEX per year		
LCOE	Levelized cost of Electricity		
LHV	Lower Heating Value		

from the authors knowledge), four studies proposed power cycle using the coupling between CSP and IGCC. Tanaka et al. and Coelho et al. [22,23] proposed a hybrid power plant where the solar resource is used as heat source in the Rankine Cycle. Nevertheless, they did not focus on the solar parameters of the plant (e.g. solar field area and solar multiple). The difference between the present study and [24,25]relies on the fact that they used the direct steam generation (DSG) to provide heat or steam for gasification and combustion processes. The present work proposes and simulate CSP/Biomass hybrid power plants and analyze it's technical and economic performance. Other point of contrast is that none of the studies published so far (at least from the knowledge of the authors) considered the possibility of syngas storage to deal with the intermittency of the solar resource, as the present study did. The syngas storage, is seen as one of the possibilities to enhance the operational flexibility in standard IGCC power plants and makes the continuous operation of the gasifier possible [26–28]. Nevertheless, this option enhances the CAPEX, O&M costs and decreases the overall efficiency [27,29]. The real feasibility of this option is still to be tested, there are lots of technical and implementation disadvantages such as: The high concentration of hydrogen in the syngas which may make tank's material brittle, as well as leakage, flammability and overall safety concern. Other operational issues such as storage pressure, size and technology can also be a hurdle as well as issues related to tar condensation, linked to high storage pressure [28]. This is the main reason why the gasification island of choice has a tar reforming section, therefore syngas can be stored with no problems related to tar condensation [30].

This study evaluates the hybridization of CSP and biomass through gasification. Three power cycles are proposed and a benchmark power plant simulated using AspenTech Hysys and the System Advisor Model (SAM), being defined as Integrated Solar Gasification Combined Cycles (ISGCC). ISGCC can be seen as a variant of the conventional Integrated Gasification Combined Cycle (IGCC). The difference between ISGCC and IGCC lies in the primary energy source, which in the case of ISGCCs is not only the gasification feedstock but also the solar resource. The proposed ISCGG cycles are: (i) Series ISGCC, where the CSP plant is placed in series with the combined cycle Heat Recover Steam Generator (HRSG); (ii) Parallel ISGCC, where the CSP plant is placed in parallel with the combined cycle HRSG and (iii) Steam Extraction ISGCC, where the steam that drives the gasification process is extracted from the steam turbine of a CSP facility. It is important to state that all the ISGCC uses CSP parabolic trough technology (see Section 3.7). A simple example of a generic ISCGG is shown in Fig. 2.

In Fig. 2 it is possible to identify three sub-cycles that comprise the ISGCC. The first cycle, in yellow, is the gasification cycle, where the biomass is gasified to produce syngas, which is burned in a gas turbine (GT). The green cycle is a Rankine Cycle, which works using flue gas from the GT as heat source. The standard IGCC is composed by these two cycles. The difference between an ISGCC and an IGCC lies on the third cycle, which is not highlighted in Fig. 2. This cycle contains the CSP Heat Transfer Fluid (HTF), which carries heat from the solar field to the Rankine cycle.

The next section presents the methodology of the study (including some common data used in the analysis), while Section 3 shows the data adopted and the results of the simulation of the three proposed designs for ISGCC. Section 4 compares the technical and economic performances of the three designs, also summarizing the main findings of the energy balances made. Finally, the last section concludes the study and indicates further studies on the subject of the analysis.

2. Methodology

2.1. Choice of the gasification technology

There are three main gasification technologies[1]: fixed bed, entrained flow and fluidized bed (bubbling – BFB and circulating –

[1] For more details see[31–33].