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Carbon exergy tax applied to biomass integrated gasification combined cycle in sugarcane industry

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A B S T R A C T

The development of technologies based on energy renewable sources is increasing worldwide in order to diversify the energy mix and satisfy the rigorous environmental legislation and international agreements to reduce pollutant emission. Considering specific characteristics of biofuels available in Brazil, studies regarding such technologies should be carried out aiming energy mix diversification. Several technologies for power generation from biomass have been presented in the technical literature, and plants with BIGCC (biomass integrated gasification combined cycle) emerge as a major technological innovation. By obtaining a fuel rich in hydrogen from solid biomass gasification, BIGCC presents higher overall process efficiency than direct burning of the solid fuel in conventional boilers. The objective of this paper is to develop a thermodynamic and chemical equilibrium model of a BIGCC configuration for sugarcane bagasse. The model embodies exergetic cost and CO_2 emission analyses through the method of CET (carbon exergy tax). An exergetic penalty comparison between the BIGCC technology (with and without CO_2 capture and sequestration), a natural gas combined cycle and the traditional steam cycle of sugarcane sector is then presented. It is verified that the BIGCC configuration with CO_2 capture and sequestration presents technical and environmental advantages when compared to traditional technology.
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1. Introduction

The need to develop technologies based on renewable energy sources, such as biomass, grows worldwide. This development aims energy mix diversification and also meeting rigorous environmental legislation and international agreements to reduce pollutant emission.

Biomass had a bad reputation for a long time. People who are not familiar with the opportunities and benefits from the use of biomass for energy and who have only little knowledge about biomass conversion technologies tend to have prejudices. People transfer such experience to new biomass energy plants and tend to think that the techniques for the use of biomass for energy are out-of-date, i.e., old fashioned, no high technology and low efficiency Ref. [28]. However, new methodologies to estimate its potential as a feasible energy source, new high efficiency energy conversion technologies presented in demonstration plants and the biomass renewability contributed to change this unfavorable image in recent years. Furthermore, availability may be very high since some industrial sectors generates large amount of biomass as by-products.

Biomass technical and economic feasibility depends on new energy conversion processes and technological improvement of traditional processes because, from a commercial perspective, there are still no high reliability technologies for small scale generation at competitive costs [12]. BIGCC (Biomass integrated gasification combined cycle) is a promising technology that may contribute to a rational and efficient biomass use, but biomass diversity in terms of physical characteristics and chemical composition (for instance, black liquor and sugarcane bagasse are very different biomass) are still barriers to overcome. These difficulties, along with biomass advantages such as renewability, low sulfur emissions and neutral carbon emissions justify studies in BIGCC technology and its potential to reduce emissions.

According to [4], Rankine-based cogeneration cycle is the foundation for energy generation in Brazilian sugar/ethanol industry. Traditionally, backpressure steam turbines are used in a typical configuration, but more advanced technological routes are

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considered nowadays due to the changes in electricity market regulation that allow exceeding power selling to the grid. The authors analyzed a steam condensing cycle and a BIGCC under different cost scenarios and concluded that BIGCC requires 48% cost reduction in order to be competitive with conventional bagasse burning plants.

Coal gasification is a dominated technology, and biomass gasification is still under development; their integration with CCS (CO_2 capture and storage) industry is not yet adequately established because the components do not currently function together in the manner required for large-scale CO_2 reduction [27]. Gasification process involves biomass devolatilization and chemical degradation in order to produce a low heating value fuel gas. Air or steam is typically used in biomass gasification, resulting in a heating value around 5.5 MJ/m^3 (n). The use of pure oxygen instead of air can provide a fuel gas with heating value up to 20 MJ/m^3 (n). However, the costs are quite high and the use of pure oxygen is only recommended to produce syngas [18].

Uddi and Barreto [24] estimated the CO_2 mitigation costs of biomass-fired cogeneration technologies with CCS considering BIGCC and steam condensing cycle. A cogeneration system based on natural gas combined cycle without CO_2 capture was taken as the reference system. Results shows that BIGCC with CO_2 capture and storage was found very energy and emission efficient and cost competitive when compared to other conversion systems.

The cost-effectiveness of imposing a carbon tax for reducing greenhouse gas emissions is discussed by Ref. [22]. New bioenergy technologies for the year 2030 are then considered, including BIGCC with and without carbon capture and storage. Results indicate that a carbon tax on fossil fuels performs cost-effectively regarded the considered policy targets (greenhouse gas emission reduction and fossil fuel substitution) if bioenergy systems with carbon capture and storage are not available.

Klein et al. [11] considered IGCC with CO_2 capture an important alternative to mitigate emissions. However, costs are high because the cycles are highly complex, especially regarding CO_2 capture and liquefying. Thus, these systems are not cost-competitive against conventional technology using coal, natural gas or even direct-firing biomass. According to Rhodes et al. (2005) [29], the power cost generated by an IGCC may be attractive if the cost of emitted CO_2 is internalized.

Recent published studies related to CO_2 capture discuss the best available technologies, mainly when coal is the fuel to be gasified [14,25], stating the appropriateness of absorption methods. Advanced concepts, as the integration of fuel cells [5] and of underground coal gasification [17] into IGCC with CO_2 capture, has been recently proposed.

A proper mechanism for taxing CO_2 emissions should take into account the plant inefficiency, so that more inefficient plants should be penalized. Exergy destruction and exergy lost are the basis for the CET (carbon exergy tax), a CO_2 taxing method proposed in the works of [20,19,1,2]. CET method relates the CO_2 emissions to the efficient use of exergetic resources and, consequently, to the plant efficiency.

This work presents a comparative analysis of thermal cycles – a traditional one, based on CST (condensing steam turbine), two advanced plants based on biomass gasification combined cycle with (BIGCC-CCS) and without (BIGCC-nCCS) carbon capture and sequestration, respectively, and a NGCC (natural gas-fired combined cycle) – by using the CET (carbon exergy tax).

For applying such method of comparison to the configurations, it was needed to develop a rule for the original CET method to compare fossil and renewable fuels, as well as the CCS. A thermodynamic and chemical equilibrium model of a BIGCC configuration for sugarcane bagasse, considering gasification with pure oxygen, was then developed. The model also embodies exergetic cost and CO_2 emission analyses through the method of CET (carbon exergy tax).

The main contributions of this work are: i) concept of a BIGCC with CCS, using pure oxygen instead of air in the biomass gasification process; ii) application of CET method to renewable thermoelectric power plants, which was not considered in the original works of [1,2]; iii) setting how biomass CO_2 emission can be treated in CET method; iv) confirming CET method as an instrument for renewable energy policies regarding biomass-fired power plants.

2. Methodology

2.1. Biomass gasification model

In this section, the biomass gasification is modeled. First, it is considered gasification with air and the model is validated against experimental results found in the literature. After validation, gasification with pure oxygen is then considered.

Biomass chemical composition can be determined through ultimate and proximate analysis according standard tests (e.g. ASTM E870). Hassuani et al. [8] presented typical results from ultimate and proximate analysis of sugarcane bagasse, as shown in Table 1.

For simplification, chlorine and mineral oxides are not considered, so that bagasse empirical formula results $CH_{15.6}N_{0.011}O_{0.75}S_{0.00083}$, with molecular weight equal to $M_b = 25.6$ kg/kmol. The biomass is considered briquette-shaped with moisture content $w^* = 5.31\%$ [8]. Gasification process is modeled according to the following hypothesis: i) steady state; ii) gasification products considered ideal gases; iii) products and reactants are in chemical equilibrium; iv) reaction takes place in an isothermal fluidized bed. The model is based in one global gasification reaction and three chemical equilibrium reactions. As a result, syngas chemical composition and its lower heating value are obtained. This syngas is then considered the prime mover fuel in the IGCC model described in Section 3.2.

Equation (1) shows the global biomass-air gasification reaction, in which w is the number of moles of water in the bagasse, m is the required number of moles of oxygen and a_i is the stoichiometric coefficient of the i-th product. Since gasification is basically a substoichiometric combustion, there is no oxygen in the reaction products.

$$\begin{aligned} &CH_{1.56}N_{0.011}O_{0.75}S_{0.00083} + wH_2O + m(O_2 + 3.76N_2) \rightarrow \\ &\rightarrow a_1CO + a_2CO_2 + a_3H_2 + a_4CH_4 + a_5H_2O + a_6SO_2 + a_7N_2 \\ &\quad + a_8C_2H_4 \end{aligned} \tag{1}$$

Three other reactions in chemical equilibrium are considered: carbon monoxide-water shifting (Eq. (2)), ethylene decomposition (Eq. (3)) and methane-water shifting (Eq. (4)).

Table 1
Ultimate and proximate analysis for sugarcane bagasse [8].

Ultimate analysis (dry basis)	
Carbon	44.6%
Hydrogen	5.80%
Nitrogen	0.60%
Oxygen	44.5%
Sulfur	0.10%
Chlorine	0.02%
Mineral oxides	4.38%
Proximate analysis	
Moisture	50.2%
Ashes[a]	2.1%
Carbon[a]	18.0%
Volatile[a]	79.9%

[a] Dry basis.

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