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

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ABSTRACT

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.

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experience to new biomass energy plants and tend to think that the techniques for the use of biomass for energy are out-of-date, i.e., old fashioned, no high technology and low efficiency Ref.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 sub-stoichiometric combustion, there is no oxygen in the reaction products.

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

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.

$$CO + H_2O \leftrightarrow CO_2 + H_2 \quad (2)$$

$$C_2H_4 + 2H_2O \leftrightarrow CH_4 + CO_2 + 2H_2 \quad (3)$$

$$CH_4 + H_2O \leftrightarrow CO + 3H_2 \quad (4)$$

Bagasse moisture content w^* is the ratio between the mass of water in the bagasse and the mass of wet bagasse. It can be related to the number of moles of water in the bagasse w according to Eq. (5).

$$w = \frac{M_b w^*}{M_{H_2O}(1 - w^*)} \quad (5)$$

The stoichiometric coefficients in Eq. (1) are determined through chemical species balances (Eqs. (6)–(10)) combined with chemical equilibrium constant from the three equilibrium reactions (Eqs. (11)–(13)), in which X_i represents the molar fraction of the i-th product (Eq. (14)). Equilibrium constants in Eqs. (11)–(13) are $K_1 = 1.136$, $K_2 = 1.810 \times 10^6$ and $K_3 = 707$ [13].

$$a_1 + a_2 + a_4 + 0.5a_8 = 1 \quad (6)$$

$$2a_3 + 4a_4 + 2a_5 + 4a_8 = 1.56 + 2w \quad (7)$$

$$2a_7 = 0.011 + 7.56m \quad (8)$$

$$a_1 + 2a_2 + a_5 + 2a_6 = 0.75 + w + 2m \quad (9)$$

$$a_6 = 0.00083 \quad (10)$$

$$K_1 = \frac{X_{CO_2} X_{H_2}}{X_{CO} X_{H_2O}} \quad (11)$$

$$K_2 = \frac{X_{CH_4} X_{CO_2} X_{H_2}^2}{X_{C_2H_4} X_{H_2O}^2} \left(\frac{P}{P_0}\right)^{-1} \quad (12)$$

$$K_3 = \frac{X_{CO} X_{H_2}^3}{X_{CH_4} X_{H_2O}} \quad (13)$$

$$X_i = \frac{a_i}{\sum a_i} \quad (14)$$

Once syngas composition is known, it is easy to calculate syngas thermodynamic properties in molar (or volume) basis, such as lower heating value (Eq. (15)) and molar mass (Eq. (16)).

$$LHV_s = \sum_i X_i LHV_i \quad (15)$$

$$M_s = \sum_i X_i M_i \quad (16)$$

2.2. BIGCC-CCS model

The BIGCC-CCS[1] configuration proposed in the present work is based on a previous configuration presented by Ref. [3]; as shown in Fig. 1. The gasification section of this configuration is similar to the actual gasifier presented in Ref. [8]; so that their experimental data can be used to validate the model.

[1] Biomass integrated gasification combined cycle with carbon capture and storage.

In order to establish a proper and more accurate thermodynamic model, the BIGCC-CCS configuration is detailed bellow and depicted in Fig. 2.

-ASU (Air separation unit) is based on a N_2/O_2 double separation column;
-Circulating fluidized bed gasifier, pressurized, with pure oxygen instead of air;
-Pre-treated biomass supplied to the gasifier;
-Syngas treatment involves drying and acid gases removal;
-CO_2 removal through physical absorption;
-CO_2 cryogenic liquefaction through mechanical compression with intercooler;

Proposed BIGCC-CCS plant is divided into four main sections: air separation, gasification, power generation and CO_2 removal. In order to provide pure oxygen for the plant gasifier, an ASU (air separation unit) is required. An intercooled compressor demands 31.5 MW of power to feed the ASU with air at 0.48 MPa (stream 2) at a specific consumption of 62 kWh/ton. ASU cryogenic cycle demands around 25.4 MW of power (equivalent to 50 kWh/ton), so that the air is liquefied for N_2/O_2 separation in a double column. After vaporization, ASU vents nitrogen to atmosphere (stream 3) and oxygen is compressed at 2.5 MPa to feed the gasifier (stream 5). The oxygen compressor demands around 8.7 MW of power (73 kWh/ton).

Oxygen from air separation section reacts with pre-treated biomass (stream 6) in the gasification section in order to produce syngas in a pressurized, circulating fluidized bed gasifier. Gasification section also involves syngas cooling, drying and acid gases removal. Part of steam required in the power generation section (stream 28) is produced by cooling the syngas from gasifier (stream 7).

Power generation section of the proposed BIGCC-CCS plant is based on a combined cycle designed to produce part of the demanded power by generating it by a gas turbine (stream 31) and a steam turbine (stream 34). Plant ancillary power related to pumps and compressors are provided by these turbines. More specifically, power from gas turbine drives O_2 compressor (stream 40) and ASU refrigeration unit (stream 41); power from steam turbine drives steam cycle pumps (streams 37 and 38), air compressor (stream 39) and CO_2 compressor (stream 39). Plant also demands water and ancillary thermal energy, mainly for equipment cooling purposes. An extraction able to provide steam at 0.5 MPa is available in the steam turbine casing, which makes the plant suitable for an eventual cogeneration application. Turbine specifications are given as follows:

Gas turbine (adapted for syngas):	*Steam turbine*:
Siemens SGT5-8000H	Siemens SST 900
Power output (ISO): 375 MW	Power output: 250 MW
Pressure ratio: 19.2	Inlet steam pressure: 16.5 MPa
Exhaust gases flow: 820 kg/s	Inlet steam temperature: 585 °C
Exhaust gases temperature: 625 °C	Extraction pressure: 0.5 MPa

Finally, CO_2 removal section separates carbon dioxide from the exhaust gases through physical absorption, as described by Ref. [3]. It must be considered that there is less experience with large-scale CCS biomass plants compared with CCS coal plants. After separation, CO_2 is compressed, liquefied and either stored through some carbon-capture technology or distributed as raw material for other industrial processes. Power required in this section is about 100 MW.

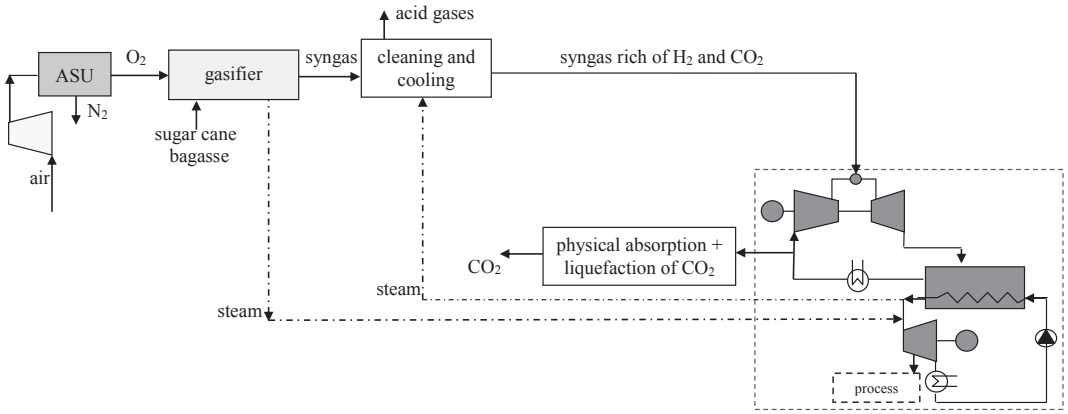

Fig. 1. BIGCC-CCS configuration according to [3].

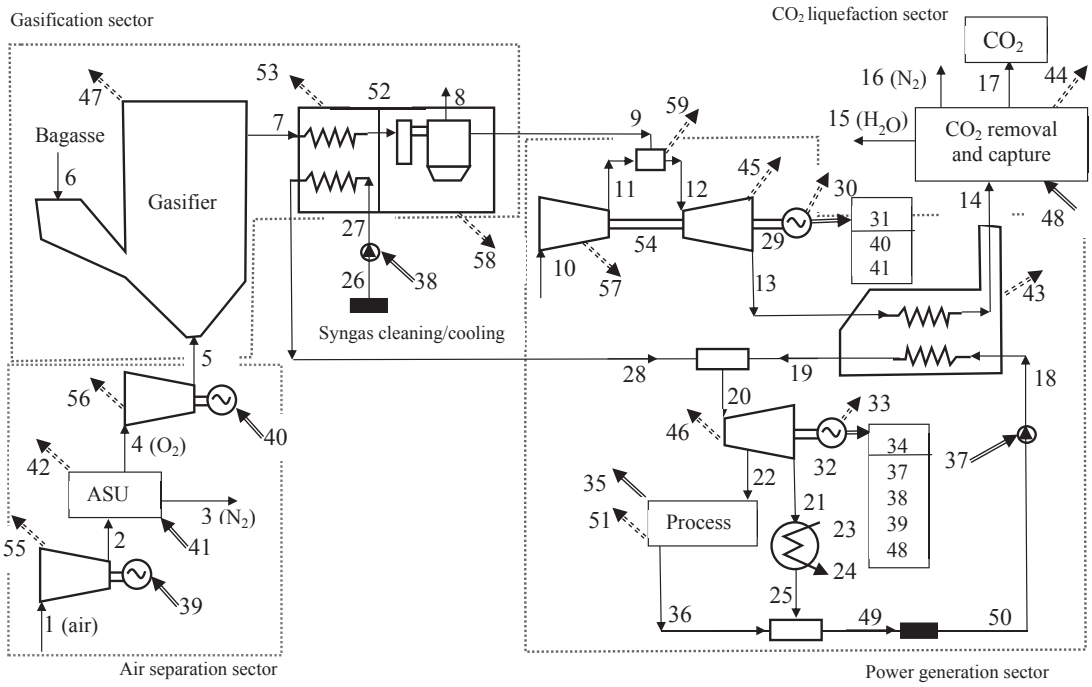

Fig. 2. Proposed BIGCC-CCS plant.

BIGCC-CCS performance is predicted through a thermodynamic model based on mass (Eq. (17)), energy (Eq. (18)) and exergy (Eq. (19)) balances in each plant component, considering steady state condition. Exergy calculation is necessary for the CET (carbon exergy tax) analysis described in the next section. Physical and chemical exergy equations were obtained from literature, being fuels and mixture of gases (synthesis gas and exhaust gas) calculated according to specific models that take into account lower heating value and molar fraction of each component, respectively [15]; reference state is stated by $P_0 = 101$ kPa and $T_0 = 298$ K. Technical data from equipment and design parameters either adopted (e.g. ambient temperature) or taken from literature (e.g. gasification pressure) provides additional information to the model, which results in a set of equation solved with EES (Engineering Equation Solver) software [7]. Results from BIGCC model are shown ahead in Section 3.2.

$$\sum \dot{m}_o = \sum \dot{m}_i \tag{17}$$

$$\dot{Q} - \dot{W} = \sum \dot{m}_o h_o - \sum \dot{m}_i h_i \tag{18}$$

$$\left(1 - \frac{T_0}{T}\right)\dot{Q} - \dot{W} = \sum \dot{m}_o b_o - \sum \dot{m}_i b_i + \dot{E}_D \tag{19}$$

2.3. CET-based penalty analysis

From contributions presented in the literature for pollutant emissions internalization, CET (carbon exergy tax) is considered in the analysis presented here. For [1], the aim of such a procedure is to assign a fee related to CO_2 emissions of energy plants, so that the

fee is based only on thermodynamic analysis (efficiency and exergy) rather than policy guidelines.[2]

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 CET model in the works of [20,19]; which relates CO_2 emissions to the efficient use of exergetic resources and, consequently, to the plant efficiency. The method requires exergy costs calculation of all streams, which is done through the TEC (Theory of Exergetic Cost) by Ref. [26]. For the sake of brevity, just a quick overview of the main equations of both CET and TEC are presented in this work, since a comprehensive presentation of both methods can be found in the literature. CO_2 cost emission is composed of the following elements:

-*Destroyed exergy cost* (Eq. (20)) is related to the sum of destroyed exergy of all j-th ($B_{D,j}$) plant components and their respective unitary cost ($c_{D,j}$).

$$C_D = \sum c_{D,j} B_{D,j} \tag{20}$$

-*Residual exergy cost* (Eq. (21)) is related to the exergy rejected from pollutant streams to the environment [20,19]. Here, the unitary cost of the j-th component $c_{R,j}$ can be seen as an inefficiency index associated to residual exergy from the exhaust gases, since this exergy is a potential product. Considering an utilization factor f_c, both destroyed and residual exergy cost determine the inefficiency penalty Π_ε (Eq. (22)).

$$C_R = \sum c_{R,j} B_{R,j} \tag{21}$$

$$\Pi_\varepsilon = f_c (C_D + C_R) \tag{22}$$

-*CO_2 emission index* (Eq. (23)) is a non-dimensional ratio between plant CO_2 emission and exergy related to the plant products B_p, also taking into account a reference CO_2 emission index I_0. Santarelli et al. [19] conceived I_C^* as a dimensionless parameter. In order to keep it non-dimensional, they established an arbitrary reference value $I_0 = 1\ kg_{CO_2}/kWh$ because they used kWh as energy/exergy unit throughout their work. In the present work it is chosen kJ as energy/exergy unit, so that I_0 is arbitrarily set to 1 kg_{CO_2}/kJ. The higher I_C^* the higher the impacts related to the plant CO_2 emissions. It can also be expressed in terms of plant exergetic efficiency ε and fuel lower heating value. Thus, three major factors penalize plant performance related to CO_2 emission: high gross emission, low exergetic efficiency and poor fuel.

$$I_C^* = \frac{\dot{m}_{CO_2}}{B_P I_0} = \frac{\dot{m}_{CO_2}}{\varepsilon LHV \dot{m}_F I_0} \tag{23}$$

-*CO_2 emission cost* (Eq. (24)) is the product of CO_2 emission index and inefficiency penalty. Borchiellini et al. [1,2], developed an approximated equation useful for preliminary analysis (Eq. (25)) from basic fuel parameters: flow ($\dot{m}_F$), heating value and carbon fraction (C).

$$C_{CO_2} = \Pi_\varepsilon I_C^* \tag{24}$$

$$C_{CO_2} \approx \frac{C \dot{m}_F (B_D + B_R)}{LHV \dot{m}_F - (B_D + B_R)} \tag{25}$$

- *CET: carbon exergy tax* (Eq. (26)) is the resulting cost per mass unit of CO_2 emitted. Borchiellini et al. [1] related it to a penalty (or cost increasing) for both power (Eq. (27)) and useful thermal energy (Eq. (28)) generated by a plant.

$$CET = \frac{C_{CO_2}}{\dot{m}_{CO_2}} \tag{26}$$

$$\Delta C_e = \frac{CET\ \dot{m}_{CO_2}}{\dot{W}_e} \tag{27}$$

$$\Delta C_t = \frac{CET\ \dot{m}_{CO_2}}{\dot{Q}_t} \tag{28}$$

In order to demonstrate CET as an instrument of energy policy that promotes the utilization of advanced energy systems [21], applied the procedure to four power plants: three conventional ones (simple gas turbine; cogeneration with regenerated gas turbine; two-pressure levels combined cycle) and an advanced one (pressurized internal reforming solid oxide fuel cell with gas turbine). The author found that just simple gas turbine plant presented power cost higher than the advanced plant for every value of carbon tax (USD/ton_{CO_2}). On the other hand, advanced plant power cost is higher than values from regenerated gas turbine cycle and two-pressure levels combined cycle for no and lower carbon tax values, but they are very close for higher carbon tax.

In this work, four configurations are compared. Two of them represent conventional technologies: a CST (condensing steam turbine) Rankine cycle burning sugarcane bagasse (Fig. 3) and a NGCC (natural gas combined cycle, Fig. 4). The other two represents advanced technologies: a biomass (sugarcane bagasse) gasification combined cycle with carbon capture and sequestration (BIGCC-CCS, Fig. 2) and a biomass gasification combined cycle with no carbon capture and sequestration (BIGCC-nCCS, Fig. 5). As far as possible, the same technical and economic conditions were assumed for all plant configurations:

-For biomass-based configurations (BIGCC-CCS, BIGCC-nCCS and CST), fuel properties are determined as presented in Section 3.1; for the NGCC configuration, natural gas properties are taken from methane for simplicity;
-All configurations are proposed as thermal power plants, so that net electric power is assumed to be about 340 MW or higher;
-It is assumed 8000 h/y of operation in all cases; biomass and natural gas prices are taken according to recent Brazilian economic scenario (natural gas price is lower than biomass price in USD/kJ); environmental conditions are P = 101 kPa and 303 K;
-It is assumed an annual interest rate equal I = 14% and n = 20 years investment, resulting in a capital recovery factor[3] equal to CFR = 0.1510 ($year^{-1}$).

TPC (Total power cost) is calculated by summing the CO_2 penalty to the LCC (levelized capital cost), as shown in Eq. (29).

[2] However, CET can be seen as an instrument of energy policy that promotes the utilization of advanced energy systems, as discussed by Ref. [21] when he applied the procedure to four conventional and one advanced energy schemes.

[3] $CRF = i(1+i)^n/[(1+i)^n - 1]$.

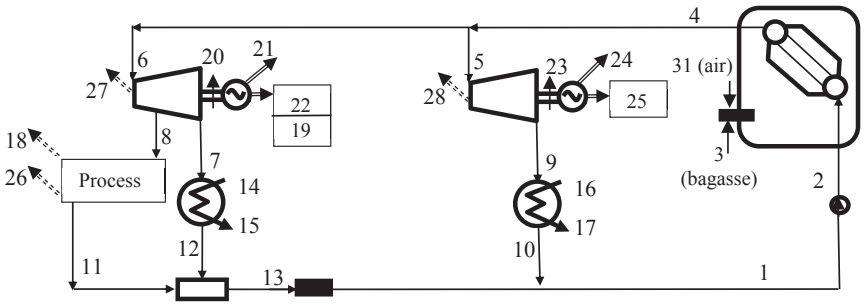

Fig. 3. CST plant.

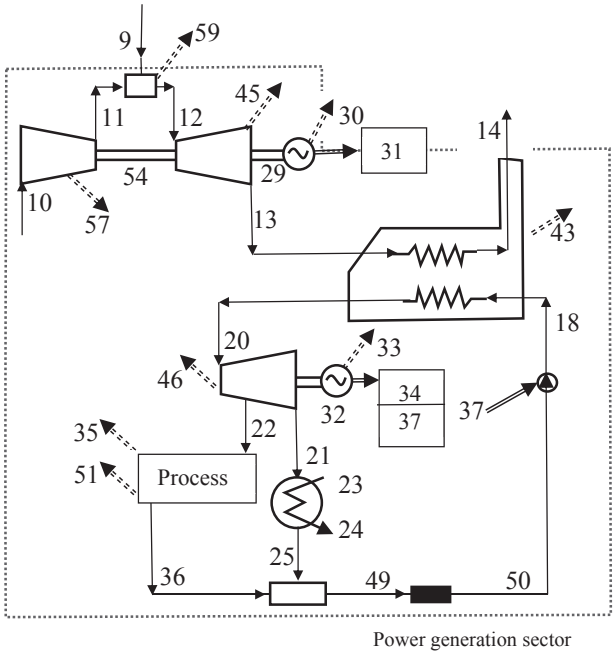

Fig. 4. NGCC plant.

LCC is related to CRF (capital recovery factor), CC (capital cost) (CC) and CF (capacity factor) (CF) according to Eq. (30).

$$TPC = LCC + \Delta C_e \tag{29}$$

$$LCC = \frac{CC \cdot CRF}{8760 \cdot CF} \tag{30}$$

In the previous works, CET was applied to fossil fuels plants (natural gas and coal), so the generated CO_2 was anthropogenic – this is the case of NGCC in the present paper. However, traditional CST technology and innovative BIGCC-nCCS, both based on sugarcane bagasse, just emit the CO_2 that was previously recovered by sugarcane during its growing, in a cyclic non-anthropogenic process. For BIGCC-CCS, sugarcane bagasse is gasified and non-anthropogenic CO_2 is captured and sequestered. Fig. 6 illustrates the described structure for fuels, technologies and CO_2 emissions.

3. Results and discussion

3.1. Biomass gasification

Stoichiometric number of moles of oxygen (Eq. (1)) is found $m_g = 1.016$. The fuel-air equivalence ratio was varied from 1 to 3, and for $\Phi = m_g/m = 2.23$, gasification model solving results $m = 0.455$ as the required number of moles of oxygen to perform the gasification reaction. Syngas composition result from biomass-air gasification model is presented in Table 2 and is validated against experimental results found by Ref. [8]. The model is then solved considering $m = 0.308$ mol of pure oxygen instead of air – this is the required number of moles of pure oxygen that result the same adiabatic flame temperature of biomass air-gasification. Such a temperature is considered a proper design parameter for an isothermal gasifier. Syngas composition obtained in this case is also presented in Table 2.

Results from biomass-air model differ up to 11% from experimental results by Ref. [8]; but the model is highly inaccurate for methane and ethylene. One of the hypotheses adopted in the model, chemical equilibrium is not observed in an actual gasifier. Thus, a kinetic model with more intermediate reactions should be adopted instead. However, methane and ethylene represent only 4% of syngas composition and errors related to their concentration do not affect significantly the lower heating value. Indeed, lower heating value found from model is 4.04 MJ/m^3 (n) against 4.10 MJ/m^3 (n) presented in Ref. [8]; corresponding to a difference of 1.46%.

3.2. BIGCC-CCS model

Results from BIGCC-CCS model presented in Section 3.2 are presented in Table 3. All streams presented in Table 3 refer to those depicted in Fig. 2. It must be advised that non-material streams (Table 3c) just identifies the occurrence of irreversible processes inside the equipment due to their inefficiencies.

The model presented in Section 3.2 applied to the CST (Fig. 3), NGCC (Fig. 4) and BIGCC-nCCS (Fig. 5) generates similar results to those presented in Table 3. These results are required for the CET-based penalty model, but they are not presented for the sake of brevity. Results referring to performance of the different cycles are summarized in Table 4, in which total net power output considers the generated power in gas and steam turbines minus the power used for driving pumps and compressors.

3.3. CET-based penalty

Results from CET model are shown in Table 5. Parameter A expresses the mass of CO_2 emitted from the combustion of 1 kg of carbon. According to the proposal of Fig. 6, A = 0 represents a non-anthropogenic CO_2 cycle for BIGCC-nCCS and CST technologies. For

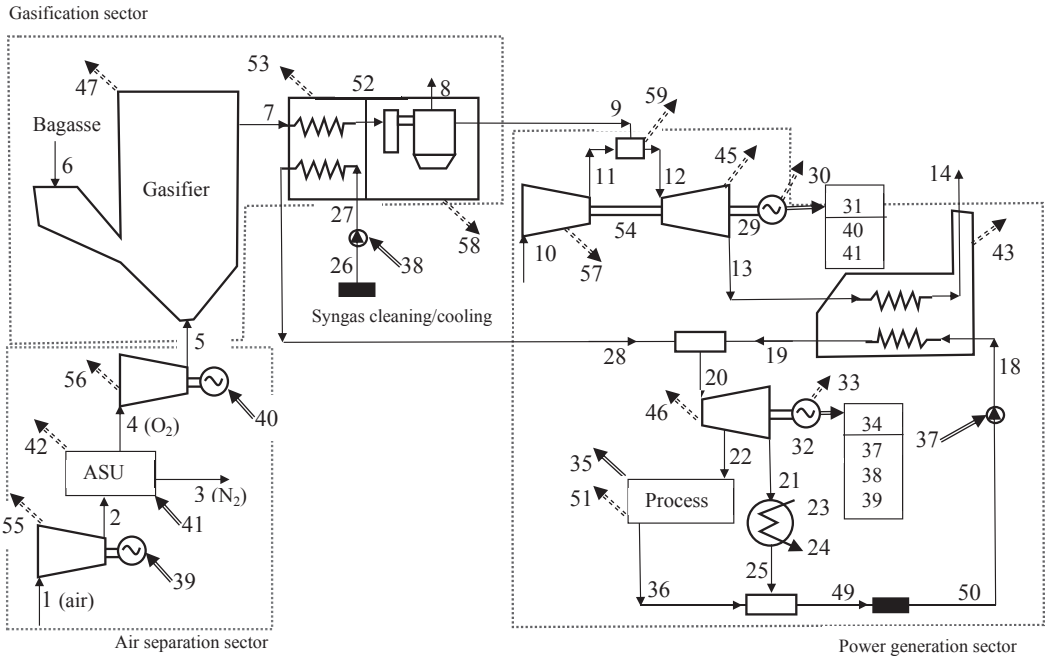

Fig. 5. BIGCC-nCCS plant.

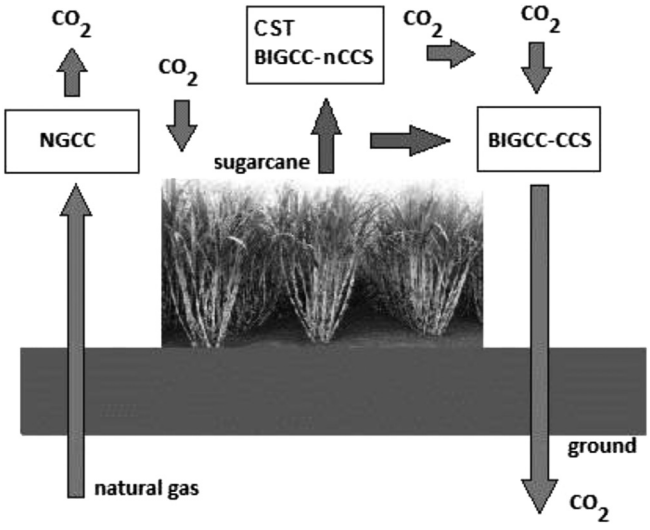

Fig. 6. Proposed structure for fuels, technologies and CO_2 emissions.

CO_2 emission index I_C^* (Eq. (23)); and CO_2 emission cost C_{CO_2} (Eq. (24)) are all negative. On the other hand, CET (Eq. (26)) is always positive regardless the technology considered.

Plant exergetic efficiency is strongly related to the inefficiency penalty parameter Π_ε (Eq. (22)). Low exergetic efficiency means the plant presents high exergy loss and destruction, resulting in a high inefficiency penalty parameter Π_ε. Thus, the higher Π_ε, the lower the exergetic efficiency. Unlike NGCC high efficiency technology, CST is heavily penalized due to its very low exergetic efficiency. However, this is not a fair comparison because the fuels in each technology are different. Now comparing Π_ε of the biomass-fired plants, it is clear that both advanced cycles based on gasification (BIGCC-CCS and BIGCC-nCCS) are far more efficient than the traditional one (CST).

Despite emitting anthropogenic CO_2 due to fossil fuel burning, NGCC technology presents the lowest CET because both exergetic efficiency and fuel heating value are high enough to compensate its high CO_2 gross emission. On the other hand, CET is very high for CST technology because it is strongly penalized by its low exergetic efficiency and fuel heating value, despite its low CO_2 gross emission. BIGCC-nCCS technology presents lower CET than CST because CO_2 gross emission is lower and exergetic efficiency is higher. When compared to NGCC technology, BIGCC-nCCS presents a much

Table 2
Results from gasification models.

i	X_i (%, dry basis)			% Error relative to [8]
	Biomass-oxygen model	Biomass-air model	Hassuani et al. [8]	
CO	44.8	18.1	18.1	0.0
CO_2	15.0	12.6	13.8	−8.2
H_2	39.8	16.4	14.8	10.8
CH_4	0.027	9.2×10^{-4}	3.2	–
N_2	0.33	52.9	49.0	7.8
SO_2	0.05	0.025	N/A	–
C_2H_4	1.1×10^{-10}	6.4×10^{-13}	0.7	–

NGCC, $A > 0$ represents anthropogenic CO_2 emission; for BIGCC-CCS, $A < 0$ indicates sequestration of non-anthropogenic carbon dioxide. Thus, for BIGCC-CCS technology, CO_2 gross emission $\dot{m}_{CO_2}$;

Table3a
BIGCC-CCS model results: material streams.

i	Description	ṁ (kg/s)	P (MPa)	T (K)	h (kJ/kg)	s (kJ/kg-K)	b (kJ/kg)
1	Air	141.4	0.10	303.0	303.20	6.87	0.04328
2	Air	141.4	0.48	521.1	524.90	6.98	199.3
3	Nitrogen	108.5	0.48	288.0	297.80	6.34	141.2
4	Oxygen	32.95	0.48	288.0	−10.62	−0.44	123.9
5	Oxygen	32.95	2.50	565.2	252.70	−0.23	331.5
6	Bagasse	90.62		303.0	–	–	20,635
7	Syngas	123.6	2.20	1123.0	–	–	10,792
8	Acid gases	13.01	2.00	673.0	–	–	787.3
9	Syngas	110.6	2.00	673.0	–	–	10,235
10	Air	1397	0.10	298.0	298.2	6.86	0.0
11	Air	1397	1.95	910.0	945.6	7.18	571.5
12	Combustion gases	1508	1.85	1573	–	–	1316
13	Combustion gases	1508	0.12	898.0	–	–	387.9
14	Exhaust gases	1508	0.11	375.0	–	–	68.83
15	Water	82.59	0.11	306.0	137.7	0.48	0.4501
16	Nitrogen	1122	0.11	388.0	403.0	7.09	19.18
17	Carbon dioxide	303.1	11.00	398.0	26.40	−0.75	526.9
18	Water	304.1	12.50	307.0	153.1	0.49	12.96
19	Steam	304.1	10.72	623.0	2896	5.88	1149
20	Steam	334.4	10.72	623.0	2896	5.88	1149
21	Steam[a]	319.4	0.01	306.0	2439	8.00	60.75
22	Steam	15.00	5.00	593.0	2984	6.31	1108
23	Water	5868	0.30	298.0	104.4	0.36	0.2006
24	Water	5868	0.10	328.0	229.7	0.77	5.921
25	Water[b]	319.4	0.01	306.0	137.7	0.48	0.3482
26	Water	30.31	0.10	305.5	135.7	0.47	0.3916
27	Water	30.31	12.50	306.5	150.9	0.48	12.90
28	Water	30.31	10.72	623.0	2896	5.88	1150
36	Water	15.00	0.01	305.5	135.6	0.47	0.2947
49	Water	334.4	0.01	305.5	135.6	0.47	0.3457
50	Water	304.1	0.01	305.5	135.6	0.47	0.2950
52	Syngas	123.6	2.11	673.0	–	–	10,259

[a] Saturated, quality x = 0.95.
[b] Saturated, quality x = 0.

Table 3b
BIGCC-CCS model results: non-material streams exergy – power and heat.

i	Description	B (MW)
29	Gas turbine net shaft work	389.5
31	Gas turbine net power	335.9
32	Steam turbine net shaft work	144.5
34	Steam turbine net power	137.3
35	Process heat[a]	9.560
37	Steam cycle pump power	5.320
38	Syngas cooling pump power	0.4618
39	Air compressor power	31.50
40	Oxygen compressor power	8.677
41	ASU cryogenic cycle power	25.39
48	Carbon dioxide compressor power	100.0
54	Gas turbine gross shaft power	1254

[a] T = 383.9 K.

Table 3c
BIGCC-CCS model results: non-material streams – destroyed exergy.

i	Description	B (MW)
30	Gas turbine generator	19.50
33	Steam turbine generator	7.226
42	ASU cryogenic cycle	34.17
43	Heat recovery steam generator	135.5
44	Carbon dioxide compressor	22.55
45	Gas turbine	157.5
46	Steam turbine	203.9
47	Gasifier	547.2
51	Process	7.054
53	Syngas cooling	157.1
55	Air compressor	3.327
56	Oxygen compressor	1.836
57	Gas turbine set compressor	66.25
58	Syngas treatment	125.9
59	Gas turbine set combustion chamber	54.95

lower CO_2 gross emission, but it is penalized by its lower exergetic efficiency and fuel heating value. Application of CET model for all technologies results no penalty charge ($\Delta C_e = 0$) for cyclic non-anthropogenic cycles, as expected. On the other hand, anthropogenic CO_2 emissions penalize NGCC plant ($\Delta C_e > 0$), whereas a negative penalty ($\Delta C_e < 0$) charge results for BIGCC-CCS plant due to non-anthropogenic CO_2 sequestration.

Power costs with CO_2 tax internalized are shown in Table 6, considering different CC (capital cost) and CF (capacity factor) found in the literature [10]. LCC (Levelized capital cost) and TPC (total power cost)[4] are estimated according to Eqs. (30) and (29), respectively. NGCC technology presents the lowest LCC because: i) its capital cost is very competitive; ii) its operating cost related to fuel consumption is low due to its high efficiency. However, NGCC penalty charge ΔC_e (Eq. (27)) is high because its emitted CO_2 is anthropogenic and not captured thereafter. It is quite interesting to note that the penalty charge ΔC_e is negative for BIGCC-CCS technology. Despite BIGCC-CCS presents the highest levelized capital cost (due to its very high capital cost), its TPC (total power cost) is lower than NGCC because the negative penalty charge represents a monetary bonus related to the non-anthropogenic carbon capture.

[4] TCP = LCC − ΔC_e.

Table 4
Cycle performance results.

	BIGCC-CCS	BIGCC-nCCS	CST	NGCC
Efficiency (1st law)	0.2915	0.2946	0.1919	0.4138
Fuel heat input (MW)	1244.0	1244.0	1774.0	1244.0
Power output (MW)				
Total net	362.3	366.5	340.4	514.8
Gas turbine set	370.0	370.0	–	389.5
Steam turbine	137.3	42.3	2 × 175.0	130.7

Table 5
CET-based penalty model results.

Parameter		BIGCC-CCS	BIGCC-nCCS	CST	NGCC
A	(kg_{CO_2}/kg_C)	−3.67	0	0	3.67
$\dot{m}_f$	(kg/s)	90.62	90.62	98.03	24.88
C_D	(USD/s)	5.39	5.24	30.87	0.21
C_R	(USD/s)	0.13	0	0.67	0.00
Π_ε	(USD/s)	5.03	4.79	28.80	0.20
$\dot{m}_{CO_2}$	(kg/s)	−76.49	0.02	0.02	68.48
B_P	(MW)	345.5	345.5	350.0	351.2
I_C^*	(−)	−0.80	0.00	0.00	0.71
C_{CO_2}	(USD/s)	−4.01	0.00	0.00	0.14
CET	(USD/ton_{CO_2})	52.46	49.89	296.28	2.01
ΔC_e	(USD/MWh)	−43.00	0.00	0.00	1.40

Penalty charge for BIGCC-nCCs is near zero, which means its TPC is neither penalized nor rewarded. Thus, its TCP is not as competitive because its CC is high.

TPC variation with interest rate is shown in Fig. 7, on which only the most favorable scenario shown in Table 6 is considered for each technology. Annual interest rate varies in the range 0–25% for 20 years life (values from Table 6 are calculated for i = 14%). It is observed that BIGCC-nCCS and CST plants present similar TPC for lower interest rate, although CST is slightly more attractive than BIGCC-nCCS for any interest rate. NGCC plant present TPC comparatively favorable relatively to the previous plants due to its high efficiency, low capital cost and rich fuel. When carbon capture and sequestration is included in the BIGCC cycle, a CO_2 emission tax charging equal to ΔC_e would make BIGCC-CCS the most attractive technology, with the lowest TPC in all the range considered. More interesting, TPC is negative for i ≲ 13%. It means that BIGCC-CCS would be fully rewarded for capturing and sequestrating carbon, regardless the power selling price. It would be an innovative business model for the power market, on which BIGCC-CCS is not a power plant that sequestrates carbon which is fully rewarded by selling power. Instead, it is a non-anthropogenic carbon sequestrating plant on which power is a by-product.

The previous discussion evinces CET methodology as a proper toll to establish energy policies that promote the use of high efficiency technologies and renewable fuels, in accordance to

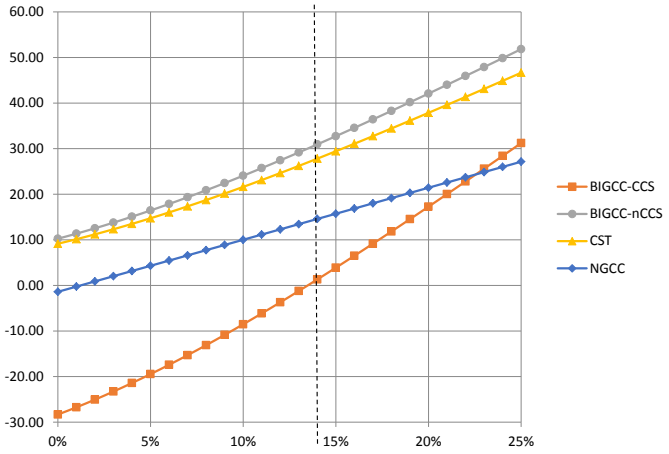

Fig. 7. TPC variation with interest rate.

Santarelli (1999) [19]. Such policies could, for instance, impose carbon taxing, provide subsides for efficient plants and stimulate investments in R&D to reduce the technology costs.

4. Conclusion

The development of technologies based on energy renewable sources must be technically adequate and satisfy the rigorous environmental legislation agreements to reduce pollutant emission. Biomass integrated gasification combined cycle emerge as a major technological innovation and was considered in this work in two different schemes: with and without carbon capture and sequestration. Two other traditional technologies were also considered: natural gas combined cycle and biomass steam cycle traditionally employed in Brazilian ethanol industry.

Carbon exergy tax method was applied in all four considered technologies. It revealed that BIGCC without carbon capture and sequestration is not economically attractive in terms of its total power cost. However, when assuming a tax related to CO_2 emissions, BIGCC with carbon capture and sequestration becomes an interesting choice because it removes non-anthropogenic carbon from the atmosphere.

The CO_2 tax is assumed as an instrument of energy policy that promotes the use of advanced energy systems. Moreover, under considered economic scenario, BIGG with carbon capture and sequestration would be fully rewarded for capturing and sequestrating carbon, regardless the power selling price. It would be an innovative business model for the power market, on which BIGCC-CCS is a non-anthropogenic carbon sequestrating plant that generates power as a by-product instead a power plant that sequestrates carbon that is fully rewarded by selling power.

Table 6
Power generated costs with CO_2 tax internalized.

Parameter	BIGCC-CCS			BIGCC-nCCS		CST			NGCC			
CC (USD/W)	2.13[a]	2.13[d]	2.56[a]	1.47[a]	1.49[d]	1.86[a]	1.07[d]	1.08[b]	0.60[a]	0.65[a]	0.92[d]	0.90[c]
CF (−)	0.67[b]	0.83[d]	0.67[b]	0.67[b]	0.83	0.67[b]	0.83[d]	0.67[b]	0.60[b]	0.60[b]	0.87[d]	0.60[b]
LCC (USD/MWh)	54.70	44.30	65.90	37.90	30.90	47.80	38.80	27.90	17.20	18.70	18.20	25.90
TPC (USD/MWh)	11.70	1.30	22.90	37.90	31.00	47.90	38.90	28.00	21.40	22.80	22.30	30.00

[a] Source [23].
[b] Source [16].
[c] Source [9].
[d] Source [6].

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