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CO_2 Capture in a Thermal Power Plant Using Sugarcane Residual Biomass

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Abstract: The decarbonization of energy matrices is crucial to limit global warming below 2 °C this century. An alternative capable of enabling zero or even negative CO_2 emissions is bioenergy with carbon capture and storage (BECCS). In this sense, the Brazilian sugar–energy sector draws attention, as it would be possible to combine the production of fuel and electricity from renewable biomass. This paper is the final part of a study that aimed to research carbon capture and storage (CCS) in energy systems based on sugarcane. The case studied is CCS in thermal power plants considering two different technologies: the steam cycle based on the condensing–extraction steam turbine (CEST) and the combined cycle integrated to biomass gasification (BIG-CC). The results for the thermal power plant indicate that the CO_2 capture costs may be lower than those in cogeneration systems, which were previously studied. The main reasons are the potential scale effects and the minimization of energy penalties associated with integrating the CCS system into the mills. In the best cases, capture costs can be reduced to EUR 54–65 per ton of CO_2 for the CEST technology and EUR 57–68 per ton of CO_2 for the BIG-CC technology.

Keywords: BECCS; bioelectricity; carbon capture and storage; carbon sequestration; climate change; negative emissions

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1. Introduction

The Intergovernmental Panel on Climate Change (IPCC) [1] recently confirmed the alarming levels of greenhouse gases (GHGs) in the atmosphere, concluding that climate change is already affecting all regions of the planet, and that continued GHG emissions will cause further global warming and irreversible changes in the main components of the climate system. In most proposed mitigation pathways to limit global warming, carbon removal is strictly required, and it is estimated that about 110 to 1100 gigatons of CO_2 must be removed from the atmosphere by 2100 [2].

The Paris Agreement, adopted in 2015, was hailed as a watershed for climate action in international policy. It is based on commitments to nationally determined contributions (NDCs) which should result in a consistent global response to climate change, keeping warming well below 2 °C this century. In fact, the long-term goal is to keep warming to 1.5 °C [3]. Following the NDCs, many countries included carbon capture and storage (CCS) in their long-term strategies to reduce emissions from the energy and industrial sectors [4]. Global emissions of GHGs need to reach net zero by 2050, which requires the contribution of significant negative emissions to offset the remaining ones [5,6]. In the energy sector, there is a portfolio of alternatives for reducing net GHG emissions, such as the decarbonization of electrical matrices, fuel switching, the electrification of industrial processes and transport systems, in addition to carbon capture and storage [2].

Regarding CCS in power plants, the database of projects provided by the Global CCS Institute [7] lists three commercial facilities: one with suspended operation (Petra Nova, in the USA, with a capacity of 1.4 million tons of CO_2 per year—$MtCO_2$), one in operation (Boundary Dam, in Canada—1 $MtCO_2$), and one under construction (Guodian Taizhou Power Station, in China—0.3 $MtCO_2$). A similar database from the International Energy Agency (IEA) [8] lists the same three projects and includes two smaller CCS facilities in the operational stage: one in China (China Energy Jinjie Power—0.15 $MtCO_2$) and one in Japan (Mikawa Power Plant—0.18 $MtCO_2$). All these power plants burn coal, except for the Japanese unit (the fuel is palm kernel shells) [9]. In recent years, assessments have been carried out on carbon capture in power plants [10–14], and, in particular, the specificities of some countries have been addressed [15–17].

The sustainable use of biomass for energy and CCS are two alternatives for mitigating emissions, and they can be combined in BECCS systems. Biomass-to-energy is reasonably common in electricity and heat generation; in general, feedstock could include agricultural and industrial residues, sewage sludge, and forest waste [18]. The most recent goal for BECCS, mentioned by the IEA [8], is that almost 3000 $MtCO_2$ must be annually captured by 2070. By 2022, BECCS systems have contributed to the effective capture of only about 1 $MtCO_2$ per year [8].

Currently, most active BECCS projects are in ethanol plants, with seven operational facilities and thirty-nine facilities in advanced development, expected to be operational by 2024–2025. Most corn ethanol plants are concentrated in the United States, accounting for approximately 95% of such facilities. In Brazil, there is an early development project centered around corn ethanol production. Additionally, Canada has a project known as the CCUS Hub in southeast Saskatchewan which involves the collection of CO_2 emissions from various sources in the Moose Jaw to Regina corridor [7].

In the power sector, only three projects were reported [7]. The Mendota BECCS project is based on oxycombustion technology to capture CO_2 from the synthesis gas combustion, produced by waste biomass gasification [19]. The Drax project is expected to be the first large-scale project operating 100% on wood-pellet biomass feedstock. The pilot plant started capturing one ton of CO_2 per day, and the aim is to capture 4.3 $MtCO_2$ per year by 2027 [7]. The Cyclus Project is currently under evaluation, with no information available regarding its operational status. A power plant based on biomass (various fuel sources such as wood chips, wood waste, bagasse, or other available alternative fuels) with a capacity of 200 MW, located in Baton Rouge, Louisiana, US, would have a negative net carbon impact [20].

Critics point out that, for the large-scale deployment of BECCS, it is necessary to overcome challenges throughout the supply chain, such as in the production of biomass, the impacts associated with land-use change (e.g., the risk of deforestation), the potential impact on the prices of food, the implantation of biorefineries, the transport and injection of CO_2, and the monitoring of potential risks involved with CCS [21,22].

To make BECCS economically viable, it is necessary to tax fossil emissions and/or remunerate stored biogenic CO_2 [23]. The IEA estimates that CO_2 capture from fermentation in association with ethanol production is currently the cheapest option, with costs ranging from 20 to 30 EUR_{2020}/tCO_2 [24]. Likewise, capture costs in biomass-based electricity generation vary from 50 to 70 EUR_{2020}/tCO_2 [25]. According to Tanzer et al. [23], fossil fuel emissions need to be taxed by an estimated 70 EUR_{2020}/tCO_2 for BECCS processes to be competitive.

The sugarcane sector in Brazil has a large amount of residual biomass available, and this suggests a significant BECCS potential. Brazil is responsible for 27% of the global production of ethanol [26], which is the most consumed biofuel in the world. Brazil currently has about 360 operating mills [27], emitting million tons of CO_2 per year, both from fermentation and biomass burning in the cogeneration processes. Moreira et al. [28] estimate a potential removal of 28 $MtCO_2$ per year through CCS, accounting only for the CO_2 from ethanol fermentation in the production of ethanol. Mills already use residual sugarcane biomass—bagasse and, more recently, straw—in conventional combined heat and power (CHP) stations, and, if CO_2 were captured and stored permanently, this would significantly improve the potential of BECCS in Brazil.

The traditional use of only bagasse has provided energy self-sufficiency to the mills. The recent transition from manual to mechanized harvesting has made straw available, and its most obvious use is also in the generation of electricity, which would allow an increase in the surplus for commercialization [29]. In the recovery of straw from the field, the agronomic effects must be considered, and the removal depends mainly on climate and soil conditions [30]. In the sugar–energy sector, bagasse and straw can be stored for use as fuel throughout the year, which would benefit the facility's capacity factor.

Considering the importance of BECCS technology to achieve global goals and, in addition, the potential for sustainable biomass production in Brazil, this paper presents the final part of a study that aimed to research the capture and storage of carbon in the combined production of liquid fuels and electricity, using the already-available biomass. The authors' first study was an evaluation of the performance and feasibility of BECCS in the Brazilian sugar–energy sector, with the CCS of carbon emitted in steam-based CHP systems, together with the capture of CO_2 produced in fermentation, in ethanol production [31]. In a second study, the BECCS technology was evaluated in a sugarcane mill considering electricity generation based on the still noncommercial biomass-integrated gasification to combined cycle (BIG-CC) technology. Both pre- and postcombustion capture routes were considered in this case [32].

Since the previous results indicated the feasibility of carbon capture, this paper presents the assessment of BECCS in a thermal power plant that would use residual sugarcane biomass. The scope includes three main assessments: (*i*) comparison with the results from previous studies, (*ii*) a biomass cost impact analysis, and (*iii*) an analysis of the scale effects.

2. Materials and Methods

The previous results indicate the technical and economic feasibility of capturing carbon in sugarcane mills, although it was not possible to achieve an optimized arrangement due to the high demand for steam both in the industrial process and for regeneration of the solvent used in the capture process. This had a negative impact on capture and was the first motivation to seek an alternative configuration, assuming a thermal power plant that operates with residual sugarcane biomass—bagasse and straw—obtained from a nearby plant and/or from neighboring sugarcane fields. In order to maintain consistency with previous studies and enable the comparison of results, the same two power generation technologies (based on steam cycles and BIG-CC) were considered.

The technical results are based on a computer simulation of a biomass-based power plant with an attached carbon capture system. Data of an existing mill were obtained considering the criteria described below. This choice was also based on making the comparison with previous results possible. Economic results are based on information available in the open literature.

2.1. Plant Localization

To assess the possible location of the thermal power plant, the basic condition is the proximity to the high availability of residual sugarcane biomass; that is, areas with plants and extensive sugarcane plantations. In this sense, data from sugarcane mills in Brazil were obtained [27] and combined with data of suitable sinks for CO_2 injection. A report known as the Brazilian Carbon Capture Atlas indicates that one of the most promising sites for geological storage is the sandstones of the Rio Bonito Formation located in the Paraná Basin in the southeast and south of Brazil [33]. Sugarcane mills located in the Paraná Basin total 247 plants, as shown in Figure 1. It was also assumed that the thermal power plant should be located close to the existing electricity grid, considering the aim of reducing connection costs [33].

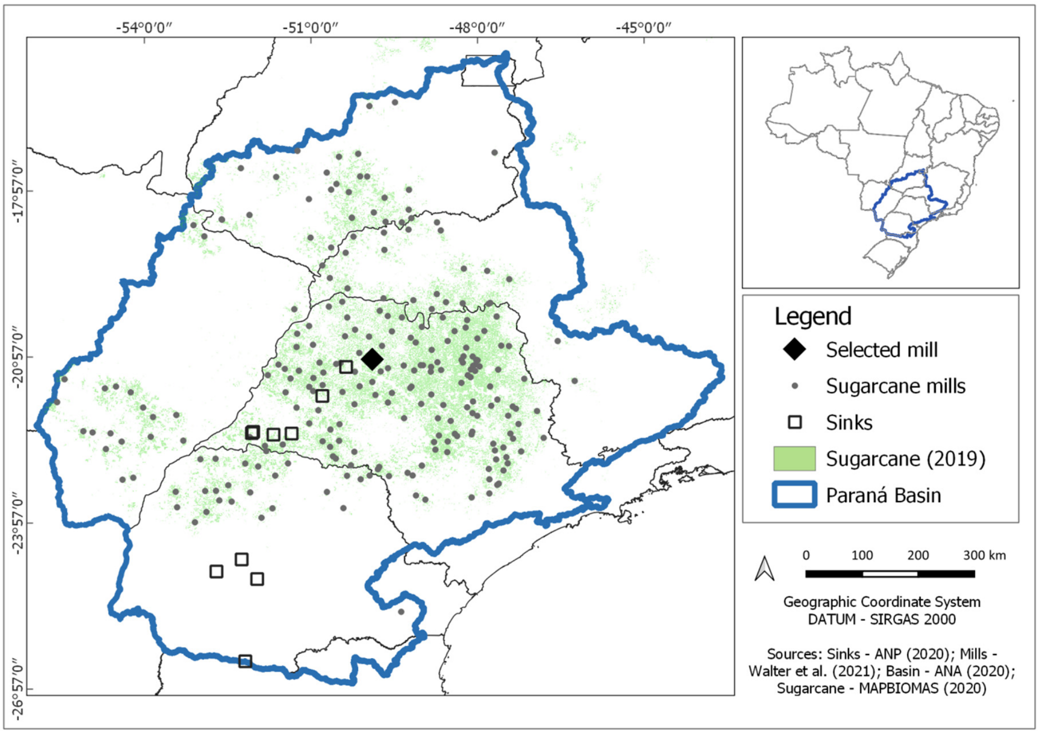

Figure 1. Sinks for CO_2 injection and the location of existing sugarcane mills in the Paraná Basin, as well as the location of the mill selected for the case study [27,33,34].

The straight-line distances from the mills to the potential sinks were calculated using geoprocessing techniques. Only mills within a circle with a maximum radius of 100 km were preselected, with the aim of reducing CO_2 transport costs through pipelines. Among the existing sugarcane mills, the selection was limited to those with a crushing capacity (in 2020) above 4.5 Mt crushed per year to maintain consistency with the previous studies. Data on the spatial distribution of sugarcane crops in 2019 [34] were used to estimate the availability of straw around each mill. Two mills meet all the criteria, and they have a sugarcane-planted area of over 150,000 ha within a 30 km radius around them; the one closest to the sink was chosen.

Thus, a sugarcane mill in the municipality of Planalto was selected, with 4.8 Mt crushed in 2020 (Figure 1). (The assumed industrial parameters are hypothetical and do not correspond exactly to the actual parameters of the mill.) The unit is located 51 km from the nearest sink (well 2-AR-1-SP, according to the nomenclature presented by the *Agência Nacional do Petróleo, Gás Natural e Biocombustíveis*—ANP), and it is 15 km from the transmission lines and 43 km from the nearest substation facility. More specifically, in 2019, sugarcane plantations occupied approximately 160,000 hectares within a radius of 30 km centered on the mill.

2.2. Biomass

It was assumed that the thermal power plant would operate with surplus biomass from the nearest sugarcane mill, with the possibility of obtaining straw from nearby plantations. The base case is the operation with surplus biomass only, and the contribution of additional biomass was considered in the scale effects analysis. The sugarcane mill was considered self-sufficient in energy and it was assumed that, in order to maximize the biomass surplus, electricity generation would only be to meet the internal consumption. The internal consumption of electricity was set at 30 kWh per ton of sugarcane [28]. To calculate surplus biomass, it was assumed that the mill operates with a conventional cogeneration system, i.e., with a back-pressure steam turbine, and only during the harvest season; Table 1 presents the main parameters assumed. In addition, aiming to maximize the biomass surplus, the cogeneration system operates with most common parameters for live steam (i.e., 65 bar; 480 °C) and the process steam demand would be reduced. The fiber content of the sugarcane plant determines the on-site availability of bagasse; in this case, 14%, which results in 280 kg of bagasse per ton of cane with a 50% moisture content [35]. The assumed lower heating value (LHV) for bagasse is 7.52 MJ/kg.

Table 1. Characteristics of the mill [28,34,35].

Parameter	Value
Milling capacity (t/h)	931
Annual harvest season (h)	5184
Mill capacity factor during harvest season	90%
Total annual milling capacity (Mt/y)	4.8
Bagasse availability per ton of sugarcane (kg)	280 (50% moisture content)
Energy demand	
Steam process requirement per ton of sugarcane (kg)	340
Electricity consumption per ton of sugarcane (kWh)	30
Steam-generation system	
Boiler efficiency (base LHV)	85%
Live steam parameters	65 bar/480 °C

Straw Availability

The straw availability was estimated based on sugarcane production within a radius ranging from 15 to 50 km around the mill, using spatialized information. The planted area of sugarcane was calculated based on the spatial distribution of sugarcane crops in 2019, according to Mapbiomas [34], and one-sixth of the area was assumed to be destined for the renovation of sugarcane plantation. For each pixel occupied by sugarcane, the SAFmaps platform database was adopted to predict the sugarcane yield, originally estimated based on historical investments in sugarcane production [27]. (The assumed values are slightly higher than the current average values due to the lack of investments in recent years in the sugarcane sector.) A total of 140 kg (on a dry basis) of straw availability in the field per ton of sugarcane was assumed [35].

On average, an amount of 4 tons of straw per hectare (dry basis) should be left in the soil for this study region, taking into account climatic conditions, soil conservation requirements, and the expected benefits for the sugarcane yield [36,37].

Two possible straw-recovery routes were considered and costs were estimated according to the distance from the cane field to the mill or to the thermal power plant. For simplicity, and to maximize the availability of biomass at the power plant, it was considered that integral harvesting takes place within a circle with a radius of up to 20 km centered on the mill, with the straw being transported together with the sugarcane. The baling system was assumed for longer distances, considering the straw would be transported directly to the power plant. The vegetable impurity in the sugarcane stalks and straw was disregarded, and no losses during the straw harvesting and transport operations were considered. Table 2 shows the estimated amount of straw available around the mill as a function of the distances.

Table 2. Amount of straw available (tons per year) for power generation according to the recovery routes.

Harvest Radius; Center at the Thermal Power Plant (km)	Total Amount of Straw Available [a] (t)	Integral (t)	Integral (%)	Baling System (t)	Baling System (%)
20	489,011	489,011	100	-	-
30	990,409	489,011	49	501,398	51
40	1,677,613	489,011	29	1,188,602	71
50	2,465,390	489,011	20	1,976,379	80

[a] Assumed properties for straw: 15% moisture and LHV 12.96 MJ/kg [35].

2.3. Power-Generation Technology

The operation of the thermal power plant was evaluated for an annual capacity factor of 90%. Two power technologies were considered: the steam cycle based on the condensing–extraction steam turbine (CEST) and the integrated biomass gasification to combined cycle (BIG-CC). The former is very common in sugarcane mills that sell surplus electricity, and the latter is a promising technology but still far from being commercial.

2.3.1. Combustion and Condensing–Extraction Steam Turbine (CEST)

In Brazilian sugarcane mills, a more advanced variant of the CEST technology has been used to generate electricity, using as fuel bagasse and straw (in relatively small amounts). In practice, the use of straw can cause serious problems in boiler operation, as its physical and chemical properties can cause fouling, slagging, and corrosion. However, here the hypothesis of the unrestricted use of straw as fuel to be burned in boilers was considered, assuming that the burning problems can be solved until the BECCS system enters the pilot and demonstration phases. This hypothesis is supported by the efforts made in recent years to understand and minimize such problems so that the continuous operation of steam generators is possible, such as the SUCRE project [30].

For the CEST technology, it was assumed that the boiler operates with the highest live steam parameters for biomass-fueled steam generators (i.e., 120 bar; 535 °C). The steam turbine has three bodies, as presented in Table 3; in the simulation procedure, it was assumed that each stage has an isentropic efficiency of 74%. Extraction takes place at the end of the intermediate pressure body, at 2.5 bar, to supply the steam required by the CO_2 capture unit.

Table 3. Assumed operating parameters of the steam turbine.

Steam Turbine Bodies	Pressure (bar)
High pressure—HP	120
Intermediate pressure—IP	21
Low pressure—LP	2.5
Condensing pressure	0.0959

The carbon content in the dry fuel was assumed to be 46.3% for bagasse and 45% for straw [38]. The CO_2 emission from combustion was estimated with the assumption of the full combustion of the biomass, and the flow of gases corresponds to the hypothesis of 30% excess air [39].

2.3.2. Biomass-Integrated Gasification to Combined Cycle (BIG-CC)

Basic information about the biomass gasification process was taken from [40]; details of the adaptation that was made are presented in [32]. A pressurized oxygen-blown gasifier was assumed to operate under the same conditions with bagasse, straw, or a mixture of them. The required oxygen was assumed to be provided by an air separation unit (ASU) integrated with the gas turbine. A low calorific gas with an assumed composition, as is shown in Table 4, is the biomass-derived gas (BDG). After the gasifier, the BDG is cooled and cleaned, and then is ready to feed in the turbine combustion chamber.

Table 4. BDG composition—gas turbine fuel (% mol).

Component	% mol
H_2	20.3
CH_4	8.1
CO	15
CO_2	23.1
N_2	4.7
Ar	0.4
H_2O	28.1
Others	0.3
LHV (MJ/kg)	7.1

The gas turbine simulation is based on the characteristics of the GT11N2, which produces 117 MW under ISO conditions. Gas turbine operation with LCV fuel corresponds to off-design conditions. In this sense, based on [41], two strategies were adopted to estimate the gas turbine operation: derating and blast-off air from the compressor. The derating corresponds to the reduction of the firing temperature to adjust the operation, and the air blast-off corresponds to an extraction at the compressor discharge (already required to feed the ASU). Table 5 summarizes the resulting main gas turbine operation parameters when the BDG is burned and compares them with its operation with natural gas on an ISO basis.

Table 5. Gas turbine (GT11N2) main parameters operating with natural gas and BDG.

Parameter	Natural Gas on an ISO Basis (LHV: 47.75 MJ/kg)	GT Operation with BDG (LHV: 7.1 MJ/kg)
Blast-off (kg/s)	-	35.42
Derating (°C)	-	37
Compressor pressure ratio	15.03	15.5
Compressor isentropic efficiency	0.907	0.901
Combustion temperature (°C)	1191	1154
Exhaust gas temperature (°C)	530.86	516

The simulation of the gas turbine and the combined cycle was performed using noncommercial software developed by the authors. The calibration of the simulation procedure was performed by comparing the results with those of the GateCycle software version 6.1.4; for more details, see [42]. Considering the fuel composition and the total carbon oxidation, the CO_2 flux in the exhaust gases was estimated.

Steam is raised in two pressure levels in a heat-recovery steam generator (HRSG); the remaining exhaust gas energy is then used to dry the biomass. Steam at 31.65 bar was required by the gasifier, and the second pressure level was set to maximize the flow that was expanded in the steam turbine. The steam required for the CO_2 capture process is extracted at 2.5 bar from the steam turbine.

2.4. Capture Unit

For both power technologies, postcombustion capture based on chemical absorption was considered. A conclusion from a previous paper [32] is that the precombustion capture is not viable compared to the postcombustion case. The capture efficiency was set at 90% in relation to the processed CO_2 flow [43,44]. The amine solvent Cansolv would be used for CO_2 removal. The postcombustion capture based on chemical absorption is the current benchmark and is used, for instance, in the Boundary Dam plant [45]. This solvent has been compared to conventional amines and showed superior kinetics, advanced absorption capacity, and lower regeneration energy [46]. Cansolv is usually blended with primary amines and additives. The solvent is recovered using steam at 2.5 bar and 140°C. The regeneration heat is estimated at 2.56 GJ per ton of CO_2 [47], corresponding to 1163 kg of steam per ton of CO_2 processed. This technology is similar to the one used by the authors in previous studies [31,42] (2.6 GJ per ton of CO_2) based on the absorption process with the MEA [48].

To maintain consistency with the authors' previous studies, and allow for the comparison of results, the CO_2 flow from the ethanol fermentation at the nearby sugarcane plant was included in the assessment. It was assumed that the combustion flow was mixed with the CO_2 stream from the fermentation and further sent to the final CCS stages: compression, transport, and storage. The CO_2 from fermentation can be considered a pure stream; therefore, no penalty was assigned because of its capture. The main considerations for estimating the amount of CO_2 from fermentation are presented in Table 6. A sugar mill with an annexed distillery (i.e., 50% of the sugarcane would be used to produce ethanol) was assumed. Energy penalties for exhaust gas treatment include pumping and blowing on all processes and auxiliaries; they were estimated at 25.84 kW per kg/s of exhaust gas [49].

Table 6. Parameters considered for estimating the CO_2 flow from fermentation.

Parameter	Value	Source
Ethanol production per ton of sugarcane (L)	86.3	[50]
Ethanol density (kg/L)	0.809	[28]
CO_2 production per kg of ethanol (kg)	0.96	[28]
Emission index per liter of ethanol (kg)	0.78	

2.5. Compression Unit

The model was proposed by Mccollum and Ogden [51]. In the first step, CO_2 was compressed from one bar to its critical pressure (73.9 bar); conservatively, an ideal gas compression divided into five stages with intermediate cooling and an isentropic efficiency of 85% per stage was assumed. In the second step, the CO_2 was already in the liquid phase, and a pump (with assumed isentropic efficiency of 85%) would be used to raise the CO_2 final pressure to 150 bar.

2.6. Transport and Storage

The transport of captured and compressed CO_2 was assumed to be via a pipeline to the nearest sink for storage, 51 km away. It was assumed that, at this distance, no recompression facility would be required.

2.7. Economic Performance Assessment

Information available in the literature was used in the economic assessment. Estimates include the investment and operation and maintenance (O&M) costs for the power unit of both technologies, for the postcombustion capture with Cansolv and the CO_2 compression; transport and storage costs at a nearby potential sinkhole were estimated from the DOE/NETL guidelines [52]. All costs are presented in Euros (EUR_{2020}). The discount rate assumed here was 8%, and the useful life of all facilities was 25 years, considering a straight-line depreciation. All capital costs refer to turn-key prices, and a location factor of 1.14 was assumed for all imported devices [53]; it was assumed that all the necessary equipment for the CEST technologies were built in Brazil.

In practice, it was assumed that the minimum selling price (MSP) of electricity from the thermal power plant should be the same as the CHP unit of the neighboring mill, without CCS, if it sold surplus electricity. The hypothesis is that the competition between electricity suppliers from biomass would impose a benchmark. Given the electricity MSP, the cost of storing and capturing CO_2 is estimated to cover all expenses (i.e., capture, compression, transport, and storage).

2.7.1. Capital Costs

Due to the information available in the literature for single capacities, the capital costs were estimated according to scaling, indicated by Equation (1); C represents the cost of capital to be estimated, Q is the capacity of the case under evaluation, α is the scale factor, and the zero subscript indicates the reference case. Unless there are specific indications, below, the scale factor used was 0.6.

$$C = C_0 \cdot \left(\frac{Q}{Q_0}\right)^{\alpha} \quad (1)$$

For the power generation technology based on CEST, capital costs were estimated in Brazilian currency (BRL) from an updated function presented in [54]. Equation (2) presents the function, already in Euros (2020), which allows to estimate turn-key investments in Brazil, including the storage of biomass and the connection to the grid (up to 40 km away).

In the equation, C represents the capital costs, in EUR/kW installed, while capacity is the total installed capacity, in MW.

$$C_{CEST} = 2726 \cdot \left(\text{capacity}\right)^{-0.334} \quad (2)$$

The capital cost for the power plant based on biomass gasification was estimated from [40]. The reference costs were assumed to be those of the nth unit, and the scale factor had values ranging from 0.5 to 0.7 according to the plant area. The estimated value includes the gasification section (gasifier island, gas clean-up, and ASU) and the HRSG (heat exchangers and steam turbines). Details for other devices are presented in [55].

A machine equivalent to the GT11N2 (i.e., same capacity—117 MW—and same net thermal efficiency—34%) was assumed to estimate the gas turbine cost. Quotes for different years [47–51] were taken and an adjusted function was used to estimate the cost in US dollars in 2020. The value was then converted to Euros [56–60].

The capital costs for the capture and compression devices were estimated from [61]. The assumed scaling factor in this case was 0.6.

2.7.2. Fuel Costs

Different hypotheses were used to assign costs to sugarcane bagasse and straw. Initially, no cost was defined for bagasse; for straw, its cost corresponded only to harvest and transport, as shown in Table 7. Further on, cost was assigned to biomass per unit of energy, as will be presented in Section 2.9.

Table 7. Biomass costs in the base case.

Biomass	Source	Harvest Radius (km)	Harvest	Harvesting and Transport Costs (EUR/GJ)
Bagasse	Surplus biomass	-	-	-
Straw	Surplus biomass	20	Integral	1.26
Straw	Collected straw	30	Bales	1.33
Straw	Collected straw	40	Bales	1.37
Straw	Collected straw	50	Bales	1.39

Sources: Adapted from OKUNO et al. [62].

2.7.3. Operation and Maintenance costs

Annual O&M costs were estimated for the gasification, electricity generation, CO_2 capture, and compression stages as a function of the total investment. These assumptions coincide with those made by the authors in previous studies [31,32]. Table 8 summarizes the assumed percentages.

Table 8. Assumptions for operation and maintenance costs [31,32].

Parameter	Annual Value
Gasification	4% of total investment
Power plant	2% of total investment
Capture unit	5.8% of total investment
Compression unit	4.6% of total investment
Transport	Calculated from [52]

In the case of CO_2 transport and storage stages, the DOE/NETL guidelines for costs estimates [52] were followed. The transport cost per ton was estimated from the reference with adaptations to maintain coherence with the cases presented here. The storage costs were directly taken in the range of EUR 7 to 18 per ton of CO_2 due to lack of information on geological storage sites in Brazil, especially for onshore options.

2.8. Comparison with Results for Cogeneration Plants

The assessment of CO_2 capture integrated into sugarcane plants (i.e., CHP plus CO_2 from fermentation) was discussed in [31,32], and those results were used in comparison with the results presented here. To make the comparison possible, the results previously presented were re-estimated to maintain consistency with the assumptions of this study. Thus, in all cases, the sugarcane mill was assumed to be an annexed distillery. All economic parameters were updated when the results were originally presented in values different from 2020. The exchange rate of 6.15 BRL/EUR for 2020 was used to convert values from Brazilian currency (BRL) to Euros.

2.9. Fuel Cost Sensitivity

Due to commercial electricity generation, it must be considered that biomass suppliers would charge more than just harvesting and transport costs, which resulted in a biomass sensitivity analysis. Thus, this impact on CO_2 abatement costs was explored. The sensitivity analysis was performed for biomass costs in the range from EUR 0.0 to 4.0 per GJ, as suggested by [63], plus the cost of harvesting and transport in the case of straw. According to [23], biomass market prices range from EUR 0 to 8.6 per GJ for planted wood residues, while in the case of residual biomass from sugarcane in Brazil, opportunity costs range from EUR 0.79 to EUR 1.37 per GJ [64,65].

3. Results and Discussion

The results presented are divided into three subsections. First, a comparison with carbon capture in a sugarcane mill is presented. Second, a sensitivity analysis on the cost of fuel was performed. Finally, the impact of scale effects was analyzed.

3.1. Comparison with Capturing in a Sugarcane Mill

Next to a sugarcane plant with a capacity equal to 4.8 Mt crushed per year, a thermal power plant would be installed. The sugarcane plant would have a cogeneration unit just to ensure self-sufficiency, and the surplus biomass would be transferred to the power plant. The results show that the mill can operate with 58% of available bagasse, not requiring straw. Thus, the surplus bagasse (42%) and all the straw available at the mill site are transferred to the thermal power plant. Table 9 presents the estimates of the surplus biomass.

Table 9. Annual surplus biomass from sugarcane mill.

Biomass	Amount (t)
Bagasse (50% moisture content)	563,201
Straw (15% moisture content)	489,011

Comparison with previous results [22,23] requires that the annual capture of CO_2 be equal, and then the amount of biomass required by the power plant was calculated. In both cases, the CO_2 stream from the fermentation in the neighboring mill was added. Table 10 presents the simulation results for both thermal power plant technologies operating with CO_2 capture.

Table 10. Technical performance of the thermal power plant.

Parameter		
Power plant technology	BIG-CC	CEST
Biomass used as fuel		
Bagasse (t/year)	563,203	563,203
Straw (t/year)	477,844	394,250
CO_2 captured per year (sources)		
Combustion ($MtCO_2$)	1.12	0.93

Table 10. *Cont.*

Parameter		
Fermentation ($MtCO_2$)	0.16	0.16
Total CO_2 captured ($MtCO_2$)	1.28	1.09
Global CCS efficiency	91%	91%
Net CO_2 emission	0.12	0.10
Power results		
Gas turbine net power (MW)	116.8	-
Steam turbine (MW)	19.7	99.7
Own power system's consumption (MW)	6.2 [a]	1.6
Gas flow treatment (MW)	10.4	17.4
CO_2 compression (exhaust gases) [b] (MW)	13.1	10.9
Electricity generation (MWh/y)	842	550
CO_2 compression (fermentation) [c] (MW)	2.9	2.9
Total electricity output (GWh/y)	827	535
Net electric thermal efficiency	29%	21%

[a] Includes gasifier consumption (ASU, O_2 and N_2 compression and boosting, fuel handling, and lock hopper). [b] Corresponding to the compression of CO_2 from the combustion flow of the thermoelectric. [c] Corresponding to the compression of CO_2 from fermentation at the neighboring ethanol plant. This stream only exists during harvest season.

Results from previous studies have been updated to allow for the proper comparison of the results. The mill has an annexed distillery and sugarcane is used in equal amounts to produce ethanol and sugar (i.e., 50% of the cane is used for ethanol).

In the BIG-CC case, almost all available biomass would be consumed, being all bagasse and 98% straw. In this case, the total annual capture would be 1.28 $MtCO_2$, and this corresponds to 91% of the total CO_2 flow. The power required for compression was estimated separately: the compression of CO_2 from biomass combustion in the thermal power plant and the compression of CO_2 produced during fermentation. The annual net electricity output would be 827 GWh.

In the CEST case, the thermal power unit would consume all available bagasse and 81% of straw. The comparison with previous results requires the consideration of a lower carbon-capture capacity (1.09 $MtCO_2$ per year), since the BECCS system previously studied in the CEST case would be installed in a mill with a lower crushing capacity (4.0 Mt of cane crushed per year). The global capture efficiency would also be 91%. The net electricity generation would be 535 GWh, which is 35% lower than in the BIG-CC case.

For simplicity, the economic assessment was performed considering a single flow of investments in year 0. Table 11 presents the cost estimates and economic results for the BIG-CC and the CEST technologies. The costs per year, except for CO_2 transport and storage (these were taken from NETL, 2019), were calculated assuming 25 years of useful life. The total investment in the BIG-CC case (n^{th} unit of the power plant) would be equivalent to EUR 3860 per installed kW, or 11% more expensive than in the CEST case (EUR 3492 per kW). In the BIG-CC case, the gasification island (gasifier plus clean-up gases and auxiliaries) represents 25% of the total capital costs and 12% of the O&M costs. The capture unit has a significant impact on the economic performance, representing 60% of the total investment in the BIG-CC case and 83% in the CEST one. For the O&M, capture expenses represent 67% of total operation costs in the BIG-CC case and 61% in the CEST case.

Table 11. Cost and economic results for the thermal power plant with CO_2 capture.

Parameter		
Power plant technology	BIG-CC	CEST
Capital cost		
Gasifier island (M EUR)	132	-
Power unit (M EUR)	79	58

Table 11. *Cont.*

Parameter		
CO_2 capture unit (M EUR)	275	246
CO_2 compression unit (M EUR)	42	38
Fuel costs (M EUR/y)	7.8	6.4
O&M costs		
Gasification (M EUR/y)	5.3	-
Power plant (M EUR/y)	1.6	1.2
Capture unit (M EUR/y)	16.0	14.4
Compression unit (M EUR/y)	1.9	1.7
Transport (M EUR/y)	3.1	3.0
Storage (M EUR/y)	9–23	8–19
Performance indicators		
Electricity price (MSP) (EUR/MWh)	42	22
CO_2 abatement cost (EUR/tCO_2)	62–73	61–76

Table 12 compares the results for the thermal power plant that operates with residual sugarcane biomass, with CO_2 capture, with the results of previous studies [22,23] in which cogeneration systems installed in sugarcane mills were evaluated. These have been updated and adjusted for correct comparison.

Table 12. Main results for CO_2 capturing in sugarcane mill or in a thermal power plant.

Parameters	**This Study**		**[32]**	**[31]**
	Thermoelectric		**Cogeneration**	
Power plant technology	BIG-CC	CEST	BIG-CC	CEST
Mill capacity (Mt/y)	-	-	4.9	4.0
Biomass used as fuel				
Bagasse (t/year)	563,203	563,203	1,372,000	1,120,000
Straw (t/year)	477,844	394,250	403,529	321,839
CO_2 captured per year (sources)				
Combustion (MtCO_2)	1.12	0.93	1.12	0.96
Fermentation (MtCO_2)	0.16	0.16	0.16	0.13
Total CO_2 captured MtCO_2)	1.28	1.09	1.28	1.09
Global CCS efficiency	91%	91%	65%	79%
Performance and economic results				
Total electricity output (GWh/y)	827	535	936	236
Electricity price (MSP) (EUR/MWh)	42	22	42	29
CO_2 abatement cost (EUR/tCO_2)	62–73	61–72	60–71	68–79

For the BIG-CC technology (CHP and power plant), the MSP of surplus electricity was estimated at 42 EUR/MWh, which is in line with the prices paid for bioelectricity in recent auctions in Brazil [66]. For the CEST technology, the estimated MSP of electricity is 22 EUR/MWh in the thermoelectric case and 29 EUR/MWh for cogeneration. The difference can be understood mainly as result of the larger electricity output, almost 300 GWh per year, and to a lesser extent due to the lower consumption of straw (which has a cost) in the thermal power plant.

For the thermoelectric cases, CO_2 abatement costs per ton of CO_2 stored ranges from EUR 62 to 73 for the BIG-CC and EUR 61 to 72 for the CEST. Comparing with the estimated (and adjusted) costs of carbon capture and storage for cogeneration cases, there is a small increase for the power plant based on the BIG-CC technology, while for the cases based on the CEST technology, the thermoelectric configuration represents an advantage. These results lead to the conclusion that the capture in thermal power plants based on residual sugarcane biomass, in principle, makes sense, which justifies further in-depth analysis.

3.2. Impact of Fuel Costs

The owners of the sugarcane mill and the thermoelectric plant are expected to be different agents, which raises the question of the impact of biomass costs on the economic results of capturing and storing carbon. This was explored by repeating the procedure that led to the results presented in Table 12 (where only the costs of harvesting and transporting the straw were considered, i.e., which are equivalent to 0.75 EUR/GJ for the BIG-CC case and 0.67 EUR/GJ for the CEST case), now varying the energy cost in the range from 0 to EUR 5 per GJ. In the case of straw, the costs of collecting and transporting (see Table 7) were added, resulting in higher values compared to bagasse.

Figure 2 shows the variation in estimated costs of CO_2 captured for different average biomass costs (bagasse and straw). Here, it was arbitrarily assumed that costs over EUR 90 per ton of CO_2 stored would lead to a noncompetitiveness scenario compared to other mitigation alternatives. This premise regarding the threshold value is also motivated by the expectation that CO_2 capture costs will decrease in the coming years [67]. In this sense, it can be concluded that the maximum (average) cost of sugarcane biomass for a BECCS thermal power unit to be feasible is 3 EUR/GJ (in the case of maximum CO_2 storage costs). This value also serves as a reference for a future feasibility analysis in the case of using other biomasses.

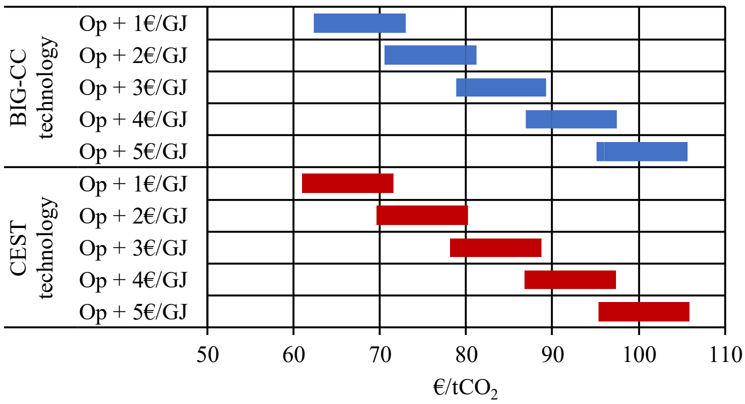

Figure 2. CO_2 abatement costs as function of biomass costs for BIG-CC and CEST technologies; Op refers to the costs of collecting and transporting straw.

3.3. Scaling Effects

Another important aspect in the analysis is the consideration of the scale effects of BECCS systems, assuming greater capacity to generate electricity and, consequently, greater capture of carbon dioxide. Electricity-generation capacity was increased by collecting the straw available in the field in a circle with a maximum radius of 50 km, centered on the thermoelectric (see Table 2). The spatial distribution of sugarcane cropping in 2019 was assumed for estimating straw availability and its location. In this case, it was assumed that the straw would be transported in bales.

Here, for simplification, it was assumed that the energy component of biomass costs is EUR 1 per GJ, and this value was added to the operating and transporting costs for straw, as reported in Table 7. The same technical parameters previously mentioned were considered both for the thermal power plants and CO_2 capture, while the costs were corrected considering the scale effect both in the power plant and in the capture unit.

3.3.1. CEST Technology

Table 13 presents results for different capacities of electricity generation based on the CEST technology. As can be seen, CO_2 abatement costs are reduced with scale effects. The increase in the cost of biomass, due to the longer transport distance, has a tiny impact on the abatement cost. Annual carbon capture is three times greater in the case of straw collection within a radius of 50 km (3.70 $MtCO_2$) in relation to the situation in which collection is restricted to a radius of 20 km (1.21 $MtCO_2$). In the best case, the abatement cost could be reduced to EUR 54–65 per ton of CO_2, which is almost 20% lower compared to the reference case.

Table 13. Results for different CO_2 capture capacities for the CEST technology.

Parameters				
Biomass used as fuel				
Collecting straw radius (km)	20	30	40	50
Bagasse used (t/year)	563,203	563,203	563,203	563,203
Straw used (t/year)	489,011	990,409	1,677,613	2,465,390
CO_2 captured per year (sources)				
Combustion ($MtCO_2$)	1.05	1.68	2.55	3.54
Fermentation ($MtCO_2$)	0.16	0.16	0.16	0.16
Total CO_2 captured ($MtCO_2$)	1.21	1.84	2.71	3.70
Global CCS efficiency	91%	91%	91%	90%
Performance and economic results				
Total electricity output (GWh/y)	608	994	1522	2128
Electricity price (MSP) (EUR/MWh)	22	22	22	22
CO_2 abatement cost (EUR/tCO_2)	69–79	63–74	59–69	54–65

3.3.2. BIG-CC Technology

Table 14 presents the results of scaling effects when electric generation is based on the BIG-CC technology. As a single gas turbine model was considered, the analysis was performed by increasing the number of modules (the same gas turbines plus the gasifier inland). The amount of biomass needed to operate two or more power modules was estimated from the requirements of the gasification unit. The same trend of reduction of CO_2 abatement costs can be observed with the scale. When straw is collected within a radius of 45 km, and the thermoelectric plant has three BIG-CC modules, the annual CO_2 capture (3.50 $MtCO_2$) is almost three times greater than when straw collection does not exceed a radius of 20 km (1.28 $MtCO_2$) and the power plant has only one module. To make a power plant with four BIG-CC modules viable, it would be necessary to collect straw beyond the 50 km radius. The CO_2 abatement cost could be reduced to EUR 57–68 per ton of CO_2, which is slightly higher than best figure for the CEST technology.

Table 14. Results for different CO_2 capture capacities for the BIG-CC technology.

Parameters			
Biomass used as fuel			
Collecting straw radius (km)	20	34	45
Bagasse used (t/year)	563,203	563,203	563,203
Straw used (t/year)	477,844	1,286,984	2,096,124
CO_2 captured per year (sources)			
Combustion ($MtCO_2$/y)	1.12	2.23	3.34
Fermentation ($MtCO_2$/y)	0.16	0.16	0.16
Total CO_2 captured ($MtCO_2$/y)	1.28	2.39	3.50
Global CCS efficiency	91%	91%	90%
Performance and economic results			
Total electricity output (GWh/y)	827	1669	2511
Electricity price (MSP) (EUR/MWh)	42	42	42
CO_2 abatement cost (EUR/tCO_2)	71–81	62–73	57–68

3.4. Feasibility in a Themal Power Plant

The comparison of the results of capturing CO_2 in thermoelectric plants burning residual sugarcane biomass with those of cogeneration systems show that the costs are not higher, and may even be lower.

Finally, a case of a stand-alone thermal power plant, without including the CO_2 from fermentation, was assessed. Tables 15 and 16 present results for the CEST and BIG-CC technologies, respectively. It can be seen that neglecting CO_2 capture from fermentation does not impact significantly the final cost. For both technologies, in the best cases, the abatement cost is slightly higher than when fermentation flow is considered, and this could be explained by the scale effects on CO_2 capturing.

Table 15. Results for different CO_2 capture capacities for the CEST technology without capturing from the fermentation flow.

Parameters				
Collecting straw radius (km)	20	30	40	50
CO_2 captured per year (sources)				
Combustion ($MtCO_2$)	1.05	1.68	2.55	3.54
Fermentation ($MtCO_2$)	0	0	0	0
Total CO_2 captured ($MtCO_2$)	1.05	1.68	2.55	3.54
Global CCS efficiency	90%	90%	90%	90%
Performance and economic results				
Total electricity output (GWh/y)	623	1009	1537	2143
Electricity price (MSP) (EUR/MWh)	22	22	22	22
CO_2 abatement cost (EUR/tCO_2)	77–87	68–79	62–72	56–67

Table 16. Results for different CO_2 capture capacities for the BIG-CC technology without capturing from the fermentation flow.

Parameters			
Collecting straw radius (km)	20	34	45
CO_2 captured per year (sources)			
Combustion ($MtCO_2$/y)	1.12	2.23	3.34
Fermentation ($MtCO_2$/y)	0	0	0
Total CO_2 captured ($MtCO_2$/y)	1.12	2.23	3.34
Global CCS efficiency	90%	90%	90%
Performance and economic results			
Total electricity output (GWh/y)	842	1684	2526
Electricity price (MSP) (EUR/MWh)	42	42	42
CO_2 abatement cost (EUR/tCO_2)	78–89	65–76	59–70

The WGIII of the Sixth IPCC Assessment Report [1] presents costs for the BECCS technology, with values between 13 and 355 EUR/tCO_2. (Values in US dollars (USD) were converted to Euro using the average exchange rate in 2020 (1.12 USD/EUR).) For the minimum values in the range, only the rigorous capture of CO_2 from fermentation in ethanol production would be competitive: under Brazilian conditions, these costs were estimated at 24 EUR/tCO_2 [28] and 23 EUR/tCO_2 [31]. However, the alternative of capturing CO_2 from fermentation at a sugarcane plant could be impacted by the scale, as CO_2 transportation represents a considerable cost factor. In fact, Tagomori [44] showed that CO_2 capture from ethanol production needs to be combined with cogeneration plants to enable the implementation of CO_2 transport infrastructure. Even so, this BECCS arrangement may not be enough, and gains in scale and operational regularity, eventually, could only be made possible with CO_2 from fossil sources [68].

As the range indicated by the IPCC is very wide, all the results reported in this paper are in the lower part. Nevertheless, as BECCS is not a mature technology (Technology Readiness Level–TRL–5-6), and there is little information about suitable sites for geological storage, there are significant uncertainties about the viability of the first units in Brazil.

CCS is one of the alternatives in the portfolio of actions for achieving climate goals. However, for similar mitigation costs, capturing carbon in a thermoelectric plant that operates with residual biomass is a more suitable option compared to capturing in a fossil fuel plant, mainly because emissions can be negative.

4. Conclusions

In this paper, the feasibility of CO_2 capture in thermal power plants using residual sugarcane biomass was analyzed, and comparisons were made with results previously presented for capture in cogeneration facilities.

The first general conclusion is that the costs are not higher, and may be even lower than when capturing in cogeneration systems. The main reasons are the potential effects of scale and the minimization of energy penalties associated with integrating the CCS system into the mills. Capture costs fall with the scale of capture, which justifies the collection of biomass in the vicinity of the thermoelectric plant. The conclusion is valid for a maximum collection radius of 50 km with the thermal power plant as the center.

The cost of biomass impacts the results, and the scenario in which residual sugarcane biomass would be valued above 2 to 3 EUR/GJ, depending on CO_2 storage costs, reduces the attractiveness of the BECCS option studied here in relation to other mitigation alternatives.

As the capacity of the thermoelectric increases, the contribution of CO_2 from fermentation to the viability of the studied alternative decreases. Thus, at the limit, it would not be necessary to define the location of the power plant due to the availability of CO_2 from the fermentation, which can give more locational flexibility to the thermoelectric. This raises the issue that CO_2 capture from fermentation, which is the most obvious opportunity, can even be handled independently.

Although this study was carried out for the use of residual sugarcane biomass as fuel, the conclusions are also valid for other biomasses provided that the distance from the planting region—and the thermoelectric plant—to the injection sinks is equivalent to that which was considered here.

Considering only the capture of CO_2, the results obtained indicate that, even in the future, assuming that they will become commercial, there should be no advantage of BIG-CC systems in relation to conventional cogeneration systems.

Finally, it is important to point out that it was assumed here that it will be possible to burn a large amount of straw to raise steam at high temperature, which today does not occur without operational problems in steam generators, even in small fractions. In the cases considered here, the amount of straw that would be burned is up to five times greater than the amount of bagasse, which clearly indicates the dimension of the problem to be faced. This is an additional challenge to overcome.

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