UNIVERSIDADE ESTADUAL DE CAMPINAS
Faculdade de Engenharia Mecânica

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Techno-economic assessment of BECCS systems in power units using residual sugarcane biomass

Avaliação da viabilidade técnico-econômica de sistemas BECCS na geração de eletricidade com uso de biomassa residual da cana

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Thesis presented to the School of Mechanical Engineering of the University of Campinas in partial fulfillment of the requirements for the degree of Doctor in Energy Systems Planning.

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"*Entonces lo vi en sus ojos. El abismo dentro de ella, igual al de las mujeres*..."

Pilar Quintana

Resumo

A alternativa de combinar bioenergia com captura e armazenamento de carbono (BECCS) oferece a perspectiva de minimizar as emissões de gases de efeito estufa (GEE) ou até mesmo retirar CO_2 da atmosfera. BECCS é uma abordagem importante para atingir a meta de 2°C como aumento máximo da temperatura média global até o final deste século. No Brasil, chamam a atenção as oportunidades de BECCS no setor sucroenergético, no qual é possível combinar a produção de combustíveis e a geração de eletricidade a partir de biomassa renovável, e integrá-las à captura do CO_2 emitido na conversão. Este trabalho tem como objetivo avaliar o desempenho técnico-econômico de sistemas BECCS na geração de eletricidade utilizando biomassa residual da cana de açúcar, no contexto brasileiro. A integração do processo de captura de carbono a uma típica usina de cana de açúcar for avaliada considerando duas tecnologias distintas de cogeração e, finalmente, foi considerada uma termoelétrica em que essa unidade utiliza biomassa excedente de uma usina próxima. O uso da biomassa residual da cana de açúcar (bagaço e palha) foi considerado devido à sua disponibilidade em larga escala e a um custo relativamente baixo nas usinas brasileiras. As tecnologias para geração de potência são o sistema convencional com turbina a vapor de extração e condensação (CEST) e a gaseificação integrada de biomassa a ciclos combinados (BIG-CC). Para o processo de captura de carbono foram comparadas as rotas de absorção química pré- e pós-combustão, ambas tecnicamente viáveis, mas que têm significativas demandas de vapor. Comparados à cogeração, os resultados para a termoelétrica são favoráveis, mas sua localização precisa ser em uma região em que potencialmente haja grande quantidade de biomassa excedente. O atual estágio de desenvolvimento tecnológico da tecnologia BIG-CC indica inviabilidade da geração elétrica e da captura de CO_2 em curto a médio prazo, horizonte em que a tecnologia CEST pode ser utilizada em projetos de demonstração. Entretanto, a alternativa de captura do CO_2 da fermentação, na produção de etanol, deve ser priorizada, pois implica poucas penalidades energéticas na indústria, tem custo relativamente baixo e pode reduzir a pegada de carbono do biocombustível.

Palavras Chave: bioeletricidade, captura de carbono, emissões negativas, cana de açúcar, biomassa, mudanças climáticas

Abstract

The alternative of combining bioenergy with carbon capture and storage (BECCS) offers the prospect of minimizing greenhouse gas (GHG) emissions or even removing CO_2 from the atmosphere. BECCS are an important approach to reach the target of 2°C as the maximum increase in the global average temperature by the end of this century. In Brazil, attention is drawn to the opportunities for BECCS in the sugar-energy sector, in which it is possible to combine the production of fuels and the generation of electricity from renewable biomass, and integrate them to capture the CO_2 emitted in the conversion. This work aims to evaluate the technical-economic performance of BECCS systems in the generation of electricity using residual sugarcane biomass, in the Brazilian context. The integration of the carbon capture process in a typical sugarcane plant was evaluated considering two different cogeneration technologies and, finally, a thermoelectric plant was considered in which this unit uses surplus biomass from a nearby industry. The use of residual sugarcane biomass (bagasse and straw) was considered because of its availability on a large scale and at a relatively low cost in Brazilian sugarcane mills. The two power technologies included, the conventional condensing-extraction steam turbine (CEST), and biomass integrated gasification to combined cycles (BIG-CC). For the capture process, pre and post-combustion routes were compared, both technically feasible but impacted by high demands of steam. Compared to cogeneration, the results for thermoelectric power are favorable, but its location needs to be in a region where there is potentially a large amount of surplus biomass. The current stage of technological development of the BIG-CC technology indicates the impossibility of generating electricity and capturing CO_2 in the short to medium term, a horizon in which the CEST technology can be used in demonstration projects. However, the alternative of capturing CO_2 from fermentation, in the production of ethanol, should be prioritized, as it implies few energy penalties in the industry, has a relatively low cost and can reduce the carbon footprint of the biofuel.

Keywords: bioelectricity; carbon capture; negative emissions; sugarcane; biomass; climate change

List of Figures

List of Tables

Abbreviations and Acronyms

ASU	Air separation unit
BDG	Biomass derived gas
BECCS	Bioenergy with carbon capture and storage
BIG-CC	Biomass-integrated gasification to combined cycle
CCS	Carbon capture and storage
CEST	Condensing-extraction steam turbine
CH_4	Methane
CHP	Combined heat and power
CO_2	Carbon dioxide
GHG	Greenhouse gases
HHV	Higher heating value
HP	High pressure
HRSG	Heat recovery steam generator
IEA	International Energy Agency
IP	Intermediate pressure
IPCC	Intergovernmental Panel on Climate Change
LCV	Low calorific value
LHV	Lower heating value
LP	Low pressure
MEA	Monoethanolamine
MSP	Minimum selling price
N_2O	Nitrous oxide
NDCs	Nationally determined contributions
TRL	Technology readiness level

Units of Measurement

°C	Celsius degree
GJ/tCO_2	Gigajoule per metric tonne of CO_2
GWh	Gigawatt-hour
h	Hour
ha	Hectare
kg	Kilogram
kg/s	Kilogram per second
km	Kilometer
kWh	Kilowatt-hour
L	Liter
MJ/kg	Megajoule per kilogram
Mt	Million metric tonne
$MtCO_2$	Million metric tonnes of CO_2
MW	Megawatt
t	Metric tonne
y	Year

Table of contents

INTRODUCTION

Context

Total greenhouse gas (GHG) emissions have increased at alarming levels since the XX century. The latest report of the Intergovernmental Panel on Climate Change (IPCC) (2021), mentions record levels for atmospheric concentrations of CO_2, CH_4, and N_2O in 2019. Its main conclusions include that climate change is already affecting every region across the globe and that the sustained emission of GHG will cause global warming and irreversible changes in the main components of the climate system. In most mitigation pathways to limit global warming, carbon removal is strictly required and it is estimated that about 110 to 1100 gigatonnes of CO_2 must be removed from the atmosphere by 2100 (ROGELJ *et al.*, 2018).

Bioenergy systems with carbon dioxide capture and storage (BECCS) fare the merging of two mitigation technologies: sustainable biomass use for energy and carbon capture and storage (CCS). Biomass-to-energy is reasonably used for electricity and heat generation; in general, feedstock could include agricultural residues, sewage sludge, and forest residues (KEMPER, 2017).

The technological variant addressed as carbon capture, utilization and storage (CCUS), when CO_2 final disposal also includes its utilization by converting it into valuable products, refers to a set of technologies that can play an important and diverse role in meeting global energy and climate goals (IEA, 2022). The CCUS process includes the capture of CO_2 from power generation or industrial facilities, the utilization into products such as fuels and chemicals, the transportation (when needed), and the injection into deep geological formations, which trap the CO_2 for permanent storage (IEA, 2020a).

BECCS technology is considered one of the most promising measures for carbon dioxide removal. In electricity generation, the target is to attain net-zero CO_2 emissions by 2050, and BECCS, among power generation technologies, is the only one able to attain zero or even negative CO_2 emissions (ROGELJ *et al.*, 2018; SANTOS; GONÇALVES; PIRES, 2019). International Energy Agency (IEA) (2022) estimated the goal for BECCS is almost 3000 $MtCO_2$ captured per year in 2070. Nowadays, effective capture by BECCS is only around 1 $MtCO_2$ per year (IEA, 2022).

Currently, active BECCS projects include only one power generation facility and five ethanol plants. The Drax project is expected to be the first large-scale project operating 100% on biomass feedstock. The pilot plant started capturing one tonne of CO_2 per day and aims to capture 4.3 $MtCO_2$ per year by 2027 as long the commercial facility begins to operate (GLOBAL CCS INSTITUTE, 2020). Deployment of BECCS on a large-scale has to overcome challenges in the whole supply chain, as producing and transporting the biomass (also addressing indirect impacts such as land use change; deforestation risk; the potential increase of food prices and food insecurity), deploying conversion processes at biorefineries, transport and injection of CO_2, and monitoring potential risks involved with CCS (BUCK, 2019).

Moreover, fossil emissions taxation and/or remuneration for stored biogenic CO_2 are needed to incentivize BECCS and make it cost-competitive with fossil fuels (TANZER; BLOK; RAMÍREZ, 2021). For BECCS options, the IEA estimates that the capture of CO_2 from fermentation in association with ethanol production is currently the cheapest option, ranging from 20 to 30 $€_{2020}/tCO_2$ (IEA, 2021). Similarly, costs from capture in biomass-based power generation range from 50 to 70 $€_{2020}/tCO_2$ (IEA, 2020a). According to TANZER; BLOK; RAMÍREZ (2021), fossil fuel emissions need to be taxed by an estimated 70 $€_{2020}/tCO_2$ for BECCS processes to be competitive.

In the case of Brazil, bioenergy already represents a fundamental alternative for the energy transition to renewable and sustainable systems (HORTA NOGUEIRA; SILVA CAPAZ; SILVA LORA, 2021). Several studies conclude that the Brazilian biofuels sector holds a major opportunity in BECCS associated with ethanol production from sugarcane (DA SILVA *et al.*, 2018; MOREIRA, J. R. *et al.*, 2016; PAULO; SZKLO; SCHAEFFER, 2016; ROCHEDO, PEDRO R.R. COSTA *et al.*, 2016; TAGOMORI *et al.*, 2018). Furthermore, it is possible to combine the coproduction of liquid fuels and electricity generation from residual biomass with CO_2 capture from both processes: fermentation and combustion. The lack of studies with this last approach motivates the evaluation carried out in this thesis, even more so due to the priority of recent publications that deal only with the capture of CO_2 from ethanol production.

In Brazil, the sugarcane industry uses residual sugarcane biomass – bagasse and straw –in conventional combined heat and power (CHP) units. The availability of straw is considered a new issue due to the transition from manual to mechanical harvesting, and its potential applications include electricity generation, which brings the benefit of increasing surplus electricity (SAMPAIO *et al.*, 2019). The amount of straw that can be recovered must consider agronomic effects and depend especially on climate and soil conditions; with good agricultural practice it is possible to recover up to 62% of available straw in the field (DE SOUZA, N. R. D. *et al.*, 2021).

On this subject, a previous assessment was performed in the master´s dissertation of the author, called “Technical assessment of BECCS systems in power units in the sugarcane sector” (RESTREPO-VALENCIA, 2018). In that work, the technical feasibility of capturing was evaluated considering the gasification of biomass integrated to gas turbine cycles. This thesis differs from the previous work mainly in the following aspects: in-depth comparison of systems based on gasification with conventional steam cogeneration systems; regarding the configuration and technology of biomass gasification; on aspects of carbon capture technology; with the deepening of the analysis of the transport and storage of CO_2; and in the economic evaluation associated with all the alternatives.

Objectives

The main objective of this work was to perform a techno-economic assessment of BECCS systems in power generation using sugarcane residual biomass. The rationale of the research was to assess BECCS opportunities in the Brazilian bioenergy context, where these opportunities could be significant in short to mid-terms. The focus was to analyze the combined production of liquid fuels and electricity using sustainable sources of biomass, while maximizing carbon capture.

The methodology and results of this thesis can contribute to the estimation of the technical and economic viability of the selected cases and to the identification of the best alternatives in the Brazilian context. It is also hoped that the information presented may be relevant to policy makers when considering carbon taxation programs and schemes for trading credits of avoided CO_2 emissions. In synthesis, as Brazil has a significant potential for BECCS technology, this thesis evaluates alternatives for the full integration of CCS with bioenergy systems, in this case considering only the use of sugarcane residual biomass.

Thesis structure

This thesis is organized into chapters addressing a sequence of interconnected topics related to BECCS technology, using residual sugarcane biomass in Brazil. The core information was presented in peer-reviewed papers by the author, already published or even submitted. The scope of the papers varies from general assessments to studies with more limited approach, aiming to identify the best capture solution (e.g. considering technologies, size of the mills, location). Three of the thesis chapters correspond to the papers mentioned, all of which were written to be sufficiently independent and allow the reader to approach them in a modular way.

This **Chapter**, **Introduction**, includes the general overview, the main objectives, and the description of the thesis structure. In addition, the rationale for evaluating BECCS in the Brazilian sugar-energy context is presented.

Chapter 1, called “Techno-economic assessment of bioenergy with carbon capture and storage systems in a typical sugarcane mill in Brazil”, is based on a paper published in the journal *Energies*. It brings a performance and feasibility assessment of BECCS system in the Brazilian sugarcane sector, lined-up with the possible deployment of CCS to current CHP systems. Cogeneration is based on condensing-extraction steam turbine (CEST), at the highest conditions for live steam, and CO_2 capture is by post-combustion technology based on monoethanolamine (MEA).

Chapter 2, entitled “BECCS opportunities in Brazil: comparison of pre and post-combustion capture in a typical sugarcane mill”, is based on a submitted paper to the *International Journal of Greenhouse Gas Control*. It refers to carbon capture integrated to a sugarcane mill considering electricity generation based on the still non-commercial BIG-CC technology (Integrated biomass gasification to combined cycle). In this case, the pre and post-combustion capture routes, both based on MEA, were considered.

Chapter 3, called “CO_2 capture in a thermoelectric plant using sugarcane residual biomass” analyzes the carbon capture in a thermoelectric plant, independent from a sugarcane mill, but using its surplus biomass. Two power generation technologies were considered and the results are compared with the studies reported in Chapters 2 and 3.

Finally, **Chapter 4** presents the final considerations of this thesis, with conclusions about the feasibility of BECCS in the sugarcane industry and on the policies and regulations necessary to promote the technology. In addition, suggestions for further research on this topic.

Assessment overview

This section presents an overview of the cases presented throughout this thesis. It aims to inform readers of the main premises that led to the definition of the BECCS systems considered.

In each chapter of this thesis, the method for the development of the research is presented, since the papers were produced independently (see Table 1), although the general objective was unique. To improve the understanding of the cases treated in this thesis, it is recommended to read the material and methods sections of Chapters 1 and 2. For the purposes of comparing the alternatives, the results of the initial works (Chapters 1 and 2) were then adjusted and these are presented in Chapter 3, along with the original material that was produced.

Table 1. Main assumptions for the assessed BECCS cases

Parameters	Chapter 1	Chapter 2	Chapter 3	
Electricity generation	Cogeneration		Thermoelectricity	
Localization of power plant	Integrated into a mill with sufficient capacity to have the BECCS system considered		Next to a mill	
Power plant technology	CEST	BIG-CC	CEST	BIG-CC
CO_2 streams captured	- All CO_2 from ethanol fermentation - From the combustion of biomass, but only the amount of CO_2 that is possible, given the limitations imposed by the thermal integration (refers to the steam necessary for the regeneration of the solvent)		- All CO_2 from combustion, plus CO_2 from fermentation from the neighbouring mill (to maintain the basis for comparison)	
Type of mill (for ethanol production)	Annexed distillery	Autonomous distillery	Annexed distillery	
Mill capacity (Mt/y)	4.0	4.9	4.8	4.8
CO_2 transport	Generic distance (100 km)		Distance from a specific mill to the possible injection point (51 km)	

An important technical assumption to be mentioned is the hypothesis of the unrestricted use of straw as fuel to be burned in boilers. The physical and chemical properties of straw can cause fouling, slagging and corrosion. Evidences are that even combined with bagasse, straw can cause serious problems in boiler operation. In this thesis it was assumed straw burning problems can be resolved until the BECCS system enters the pilot and demonstration phases. This hypothesis is supported by the efforts made in recent years to study the phenomena and propose new configurations to guarantee the continuous operation of steam generators, and in this sense, the SUCRE project should be highlighted. The main operational problems are briefly discussed in APPENDIX A.

Finally, in all cases it was assumed that the capture of CO_2 impacts the operation of the electricity generation systems (cogeneration or thermoelectric) and that the revenue from the sale of the capture service must cover the costs of the CCS system and the lost revenue of the sale of electricity, due to all energy penalties. Minimum prices for the sale of capture credits were estimated. In APPENDIX B, the main economic parameters considered in this study are presented. The assumptions reflect taxes and charges levied on investments in the Brazilian sugarcane industry.

1. TECHNO-ECONOMIC ASSESSMENT OF BIOENERGY WITH CARBON CAPTURE AND STORAGE SYSTEMS IN A TYPICAL SUGARCANE MILL IN BRAZIL[1,2]

Abstract

For significantly reducing greenhouse gas emissions, those from electricity generation should be negative by the end of the century. In this sense, bioenergy with carbon capture and storage (BECCS) technology in sugarcane mills could be crucial. This paper presents a technical and economic assessment of BECCS systems in a typical Brazilian sugarcane mill, considering the adoption of advanced—although commercial—steam cogeneration systems. The technical results are based on computational simulations, considering CO_2 capture both from fermentation (released during ethanol production) and due to biomass combustion. The post-combustion capture technology based on amine was considered integrated to the mill and to the cogeneration system. A range of energy requirements and costs were taken from the literature, and different milling capacities and capturing rates were considered. Results show that CO_2 capture from both flows is technically feasible. Capturing CO_2 from fermentation is the alternative that should be prioritized as energy requirements for capturing from combustion are meaningful, with high impacts on surplus electricity. In the reference case, the cost of avoided CO_2 emissions was estimated at 62 €/t CO_2, and this can be reduced to 59 €/t CO_2 in case of more efficient technologies, or even to 48 €/t CO_2 in case of larger plants.

Keywords: bioelectricity; carbon capture; negative emissions; sugarcane; biomass; climate change

[1] Published in: RESTREPO-VALENCIA, S.; WALTER, A. Techno-Economic Assessment of Bio-Energy with Carbon Capture and Storage Systems in a Typical Sugarcane Mill in Brazil. *Energies*, v. 12, n. 6, p. 1129, 2019.

[2] The published paper is an extension of the paper “A. Techno-Economic Assessment of BECCS Systems in the Brazilian Sugarcane Sector”, presented at the 13th Conference on Sustainable Development of Energy, Water and Environment Systems—SDEWES Conference, 30 September–4 October, Palermo, Italy

1.1.Introduction

In order to maintain 2°C as the maximum increase in the global average temperature, the levels of atmospheric concentrations must be kept below 450 ppm of CO_{2eq} during the 21st century (IPCC, 2014). Therefore, worldwide emissions of CO_2 have to be drastically reduced in the coming decades, inducing deep changes in the energy systems (IEA, 2016b). This scenario requires that emissions from electricity generation should be negative by the end of the century, with fast progress in energy efficiency and promotion of low-carbon technologies. In this context, carbon capture and storage (CCS) is crucial because it represents a process by which large amounts of carbon dioxide can be captured and stored for the long term (IPCC, 2014).

The CCS technology involves four main steps: conditioning processes to separate CO_2 into a pure stream, carbon capture itself, its compression and, finally, storage for long term periods (IPCC, 2014). In the case of CCS applied to power units, significant losses in efficiency are expected; for instance, the Intergovernmental Panel on Climate Change (IPCC) indicates a 9% net reduction in efficiency for coal-fired power plants (pulverized) and 7% for combined cycle gas-fired power plants (IPCC, 2014).

Post-combustion technology consists in the removal of CO_2 from the exhaust gases. Capture by absorption is recognized as the reference technology (IEA, 2016a; VAN DER SPEK; RAMÍREZ; FAAIJ, 2017) and considered mature for power plants (VAN DER SPEK; RAMIREZ; FAAIJ, 2016). The removal from flue gases uses a solvent, generally amines, to absorb CO_2 molecules, being CO_2 then released by heating or drastic pressure reductions (LUIS; VAN DER BRUGGEN, 2013). Flue gases need to be cooled before getting in contact with the solvent: the temperatures must be between 40 and 60°C at the entrance of absorption columns (PEETERS; FAAIJ; TURKENBURG, 2007). Costs and energy requirements—also called energy penalties—from a CCS unit using absorption capture depends mainly on the solvent properties. It is estimated that the heating for solvent regeneration is responsible for over 25% of the energy penalty when compression is included (PEETERS; FAAIJ; TURKENBURG, 2007).

Combining bioenergy with carbon capture and storage (BECCS) offers the prospect of energy supply with net negative emissions and is clearly an important approach to reach the target of 2°C. BECCS combines production of fuels and electricity from renewable biomass with carbon capture and storage of the CO_2 emitted when biomass is converted (IEA, 2016b). As the CO_2 is removed from the atmosphere during the growth of the raw material, life-cycle absolute emissions of BECSS could be negative (KEMPER, 2015). In this sense, BECCS technology applied in sugarcane mills would be fundamental, contributing with very low greenhouse gas (GHG) emissions in both the transport sector (with avoided emissions due to the displacement of fossil gasoline) and in electricity generation (MOREIRA, J. R. *et al.*, 2016).

The production of ethanol (via the fermentation of sugars) releases a pure stream of CO_2, which means there is no penalty for its separation in the CCS process. This is the most obvious option to capture CO_2 in sugarcane mills, and it is estimated that, considering the ethanol production figures of 28.5 million m^3 in Brazil, it would be possible to reduce CO_2 emissions by 27.7 million tonnes per year (MOREIRA, J. R. *et al.*, 2016). Carbon capture in sugarcane mills could at least double—or triple—with the adoption of CCS technologies in cogeneration systems in which residual biomass is burned—usually bagasse, and more recently, bagasse combined with straw.

This work focuses on assessing the technical and economic impacts of BECCS in a typical Brazilian sugarcane mill. First, a hypothetical sugarcane mill was selected to perform the evaluation that considers advanced steam cogeneration systems. A literature review was conducted to select the CCS technology and obtain representative data to model the integration of the CCS unit with the cogeneration plant. The feasibility analysis is based on typical costs (i.e., investments, operation and maintenance costs) and efficiencies, and the final assessment is based on the costs of CO_2 avoided emissions.

1.2. Materials and methods

1.2.1. Cogeneration plant

A typical Brazilian sugarcane mill, but rather representative among the more than three hundred existing mills, was considered for this study, with a 4 Mt/y (million tonnes of sugarcane crushed per year) milling capacity. The cogeneration unit would be fully integrated to the mill to supply electric power and steam to the industrial process, and also maximizing surplus electricity. The steam demand for both sugar and ethanol production was assumed equivalent to 340 kg of steam (at 2.5 bar and 137°C) per tonne of sugarcane; this is the minimum consumption of steam currently considered economically viable (SEABRA *et al.*, 2010). The power plant would operate along the whole year (with 90% capacity factor), being as a cogeneration unit during the harvest season and as a single power plant during off-season. Biomass would be stored to assure the operation during off-season and this is already a common practice for mills that generate electricity throughout the year; in general, mills have area available for this, and the costs are not prohibitive. The cogeneration technology is the one known as condensing-extraction steam-turbine (CEST), with live steam at the highest possible pressure and temperature (120 bar/535°C is the state-of-art in Brazilian sugarcane mills, according to (MOREIRA, J. R. *et al.*, 2016)).

The CEST technology is very common in modern sugarcane mills. Bagasse used to be the only fuel but, recently, a blend of bagasse and straw has been used (PEDROSO *et al.*, 2017) due to the growing straw availability at the mill site as a consequence of mechanized harvesting. Table 1.1 presents a summary of the main characteristics of the reference mill operating with CEST system and burning biomass—bagasse and straw—as fuel. Bagasse availability is defined by the fiber content of the sugarcane plant (14%), i.e., 280 kg of bagasse with 50% moisture per tonne of cane. As for straw its availability at the mill was considered 50% in relation to the total amount available at the field, resulting 161 kg per tonne of cane (with 13% moisture).

Table 1.1 Characteristics of the reference mill and the power plant.

Parameter	Value
Power plant annual capacity factor	90%
Milling capacity (t/h)	772
Annual harvest season (h)	5184
Mill capacity factor during harvest season	90%
Total annual milling capacity (Mt/y)	4.0
Bagasse availability per tonne of sugarcane [a] (kg)	280 (50% moisture content)
Straw availability per tonne of sugarcane [b] (kg)	161 (13% moisture content)
Energy demand	
Steam process requirement per tonne of sugarcane (kg)	340
Electricity consumption per tonne of sugarcane [c] (kWh)	30
Cogeneration system—CEST	
Boiler efficiency (base LHV)	85%
Live steam parameters	120 bar/535°C
Isentropic efficiency of the steam turbine (per body)	79%

Sources: [a] (PEDROSO *et al.*, 2017) for bagasse's LHV 7.52 MJ/kg; [b] (PEDROSO *et al.*, 2017) for straw's LHV 12.96 MJ/kg; [c] (MOREIRA, J. R. *et al.*, 2016).

The CEST system was modelled in a non-commercial software able to simulate its integration with sugarcane mills and to estimate electricity generation (WALTER *et al.*, 2005). The current experience with straw use as fuel has shown that problems like slagging, fouling and surface corrosion are common when the straw share is above 15–20% in the fuel blend (mass basis). These problems are due to biomass and their ash compositions, which have much more chlorine, CaO and K_2O in the case of straw compared to bagasse (BIZZO *et al.*, 2014). As it is predicted that in the considered case straw would represent about one third of the fuel input, the hypothesis is that the problems mentioned would be solved in the future. Biomass consumption—bagasse and straw—would be distributed along the year to assure fuel supply according to system's requirement.

The emissions of CO_2 from combustion were estimated considering full combustion with 30% excess air (LI *et al.*, 2015), and carbon content 48.6% in the dry fuel for both bagasse and straw (WALTER; ENSINAS, 2010). For estimating CO_2 from fermentation, it was assumed a sugar mill with a medium to large annexed distillery (i.e., 50% of the sugarcane would be used to ethanol production). A typical Brazilian mill with such a capacity (4 Mt/y) produces both ethanol and sugar with some flexibility (in general, each output varies between 40% and 60%; basis is the sugarcane input) (MOREIRA, M. M. R., 2016). Therefore, CO_2 from fermentation was calculated for an ethanol production of 86.3 L per tonne of sugarcane (MACEDO; SEABRA; SILVA, 2008) and a CO_2 production of 0.96 kg per kg of ethanol (MOREIRA, J. R. *et al.*, 2016), resulting in an emission index 0.78 kg of CO_2 per liter of ethanol (calculated for an ethanol density of 0.809 kg/L).

1.2.2. CCS unit

Carbon dioxide both from fermentation and from biomass combustion were considered to be processed in a CCS unit. CO_2 from the combustion passes through the complete CCS process (referred to as absorption, regeneration and compression), while CO_2 from fermentation only passes through the compression steps. These two streams are combined in the transportation and storage stages. It was assumed a post-combustion technology based on capture with monoethanolamine (MEA).

1.2.2.1. MEA Technology

Capture process by absorption is the reference technology and MEA is the incumbent solvent used. Absorption characteristics of the solvent determine energy penalties and impact the economic feasibility of capturing. In this study, parameters of the capture process based on MEA technology were taken from (PEETERS; FAAIJ; TURKENBURG, 2007). Solvent regeneration was considered using steam extracted at the medium-pressure stage of the steam turbine, that coincidentally is the same pressure required by the industrial process (i.e., 2.5 bar, 137°C). The three levels of heat requirement for solvent regeneration are related with the different stages of technology development: 4.4 GJ/t CO_2 (1998 kg of steam per tonne of CO_2); 2.6 GJ/t CO_2 (1180 kg of steam per tonne of CO_2); and 1.6 GJ/t CO_2 (726 kg of steam per tonne of CO_2). It was assumed 90% as the maximum possible capture rate in the CCS unit. Absorption and regeneration take place in the unit hereafter referred to as CCS. Power requirement for flow gases treatment (at the CCS unit) was estimated at 25.84 kW per unit of exhaust gas flow, in kg/s (KHORSHIDI *et al.*, 2016). This figure includes electricity requirement for pumps and blowers, capture pre-treatment pumping, cooling water pumping and blower duties and, finally, solvent pumping duties.

1.2.2.2. Compression Unit

After CO_2 separation from the exhaust gases, it goes to the compression unit, being its power requirement estimated from (MCCOLLUM; OGDEN, 2006). CO_2 is compressed from 1 bar to 150 bar in order to be transported through a pipeline. Compression is divided into two steps: first compression from 1 bar to the CO_2 critical pressure (73.9 bar), and then, in the liquid phase, a pump can be used to boost final pressure. First step was assumed as an ideal gas compression in 5-stages with intermediate cooling, and 85% isentropic efficiency per stage. Pumping requirement was calculated with isentropic efficiency of 85%. Power requirements were considered for each CO_2 stream.

1.2.3. Economic performance assessment

Cost estimations were done based on a literature review for each technology: CEST system, CCS based on MEA technology, CO_2 compression and CO_2 transport and storage at a nearby saline aquifer. All costs are presented in $€_{2014}$ in order to be coherent with the references used for CCS systems. For all equipment the useful life is 25 years, and the discount rate considered in the base case is 10% per year. This discount rate was chosen because it is a compromise taking into account the investments on generating electricity with biomass—annual rates of less than 10% would make investments more difficult—and the investments on carbon capturing and storage—in this case, due to the technology stage, the feasibility is related to a discount rate as low as possible. In any case, the results for the discount rate of 8% per year are also presented (see Section 1.3.2) in order to make comparisons possible with what has been published. For electricity generation, the feasibility was evaluated based on the minimum selling price (MSP). In the case of CO_2 capture, the minimum credit price (i.e., the income obtained by selling the credits of capturing CO_2) was estimated to cover all costs, including electricity that is not sold due to energy sanctions imposed by CCS.

1.2.3.1. Power Plant Capital Costs

The cogeneration plant at the sugarcane mill aims at self-sufficiency and the sale of surplus electricity to the grid. Capital costs were estimated ($/kW) from an updated function adapted from (GOUVELLO, 2010), which estimates turn-key investments in Brazilian currency (R$), including storage of biomass and connecting costs to the grid, according to

Equation (1.1). Values in R$$_{2014}$ were converted into Euro using the exchange rate by the end of 2014 (3.23 R$/€):

$$C_{CEST} = 3578 \cdot (capacity)^{-0.334} \tag{1.1}$$

where C represents the specific capital costs, in €/kW installed for the CEST technology, and capacity is the total installed *capacity* in MW.

1.2.3.2. CCS Unit and Compression Unit Capital Costs

For the CCS unit and the compression unit, scaling—according to Equation (1.2)—was used to estimate capital costs (scale factor 0.6); scaling is function of CO_2 capturing capacity (CO_2 flow going to CCS and to the compression unit). Values from (VAN DER SPEK; RAMÍREZ; FAAIJ, 2017) were taken to estimate the parameters of units based on MEA technology. The costs of the three different technology levels were considered:

$$C = C_{ref} \cdot \left(\frac{Q}{Q_{ref}}\right)^{\alpha} \tag{1.2}$$

where C represents the capital cost, Q the capacity, α is the scaling factor and ref indicates the reference case.

1.2.3.3. Transport and Storage Capital Costs

In this study, CO_2 storage was considered to be at the geological formation Rio Bonito, located in the south and southeast regions of Brazil (KETZER *et al.*, 2016). CO_2 injection shall be at least 1200 m below surface (MOREIRA, J. R. *et al.*, 2016). It is assumed that geological conditions are adequate to keep CO_2 stored for centuries, as required to make CCS a real alternative to mitigate GHG emissions.

Capital costs for transport and storage were estimated from (MOREIRA, J. R. *et al.*, 2016). It was assumed a pipeline with 10 km length, hypothesis that is coherent with the assumption that sugarcane mills are located nearby existing saline aquifers. Storage capital costs include a preliminary assessment of three wells drilled at 1200 m deep, which is a practical assumption to find a reservoir with appropriate conditions to long term storage.

1.2.3.4. Fuel Costs

As it was mentioned in Section 1.2.1, bagasse and straw are the biomasses burned in the boiler. No cost was attributed to the bagasse, as it is already available at the mills. This assumption was taken to resemble regular practices. In specific cases, mills have the opportunity to sell some surplus bagasse to other consumers, depending on the location and the amount available. For the use of straw, the combined cost of collecting and transport to the mill was attributed, summing-up 17.76 € per tonne of straw (CARDOSO, 2014).

1.2.3.5. Operation and Maintenance Costs

Operation and maintenance costs (O&M) of CO_2 capture (CCS and compression units) are based on (VAN DER SPEK; RAMÍREZ; FAAIJ, 2017) and were estimated, as annual values, as function of the total investment. Annual O&M costs for the cogeneration plant were assumed according to the current practices in Brazil (GOUVELLO, 2010). For CO_2 transport and storage, as a simplification, annual O&M costs were assumed at 2% of the total investment. Table 1.2 presents assumptions for O&M in this study.

Table 1.2 Assumptions for operation and maintenance costs.

Parameter	Annual value as function of the total investment
Cogeneration system—CEST	2%
CCS unit	5.8%
Compression unit	4.6%
Transport and storage	2%

1.2.4. Scaling effects

The previous sections presented the hypothesis for assessing the feasibility of BECCS in sugarcane mills. Scaling effects on milling capacity were explored as a significant impact on capital costs is expected. For this reason, it was also considered a smaller milling capacity (2 Mt/y) and a larger mill (8 Mt/y). Annual milling capacity of 2 Mt of sugarcane crushed could be considered as an average mill in Brazil; (MOREIRA, M. M. R., 2016) reports that 39% of sugarcane mills are close to this capacity. Bigger capacities, as 4 Mt/y and 8 Mt/y, are less usual—4 Mt/y is more common and few units are close to 8 Mt/y—but larger mills is the general tendency in the future.

1.2.5. GHG emissions due to the supply of biomass

It was assumed, by simplification, that both bagasse and straw are carbon neutral, i.e., there would be no GHG emissions due to the biomass used as fuel in the cogeneration unit. Many life cycle assessments of ethanol from sugarcane and electricity generation from bagasse assume that the bagasse is carbon neutral (it would be a residue) being all the environmental burdens imposed on ethanol and sugar, as the main final products (MACEDO; SEABRA; SILVA, 2008; SEABRA *et al.*, 2010; SEABRA; MACEDO, 2011). In the case of straw, as currently there is no other use other than as fuel on the site of the mill, and because the straw is derived from a mechanized harvest that is a new practice, it is common to impose to the straw a share of the emissions of the sugarcane harvest and its transport to the mill. In this sense, the hypothesis assumed in this document is optimistic regarding the benefits of carbon capture related to cogeneration systems. However, it is important to bear in mind that approximately 15–25% of the amount of straw that is supposed to be available as fuel at the factory site (HERNANDES; LEAL, 2020) is anyway transported to the plant as impurities and, in addition, the straw represents approximately one third of the total energy input. Therefore, the simplification carried out does not imply a great distortion with respect to the benefits of carbon capture, and was considered reasonable for a preliminary evaluation of BECCS in a sugarcane mill.

1.3. Results and discussion

This section is devoted to present and discuss the results and is divided into three parts. The first part presents the technical performance of the integrated BECCS systems to a hypothetical sugarcane mill. As previously mentioned, three levels of heat demand for solvent regeneration—related to the different stages of the technology—were evaluated. The second part focuses on the feasibility of carbon capture in a sugarcane mill. Finally, in the third part the effects of scale are analyzed.

1.3.1. Technical performance

The simulated cogeneration system has a steam turbine with one controlled extraction at 2.5 bar and condensation of the remaining flow. Five cases were assessed: the reference case, i.e., the cogeneration plant without CCS; case 1—cogeneration plant with CCS only from CO_2 of fermentation; case 2—cogeneration plant with CCS from both fermentation and combustion, and solvent regeneration requiring 4.4 GJ/t CO_2; case 3—cogeneration plant with CCS (fermentation and combustion CO_2) and 2.6 GJ/t CO_2 as heat requirement; and case 4—cogeneration plant with CCS (fermentation and combustion CO_2) and 1.6 GJ/t CO_2 as heat requirement. For all cases, simulation includes harvest and off-harvest seasons.

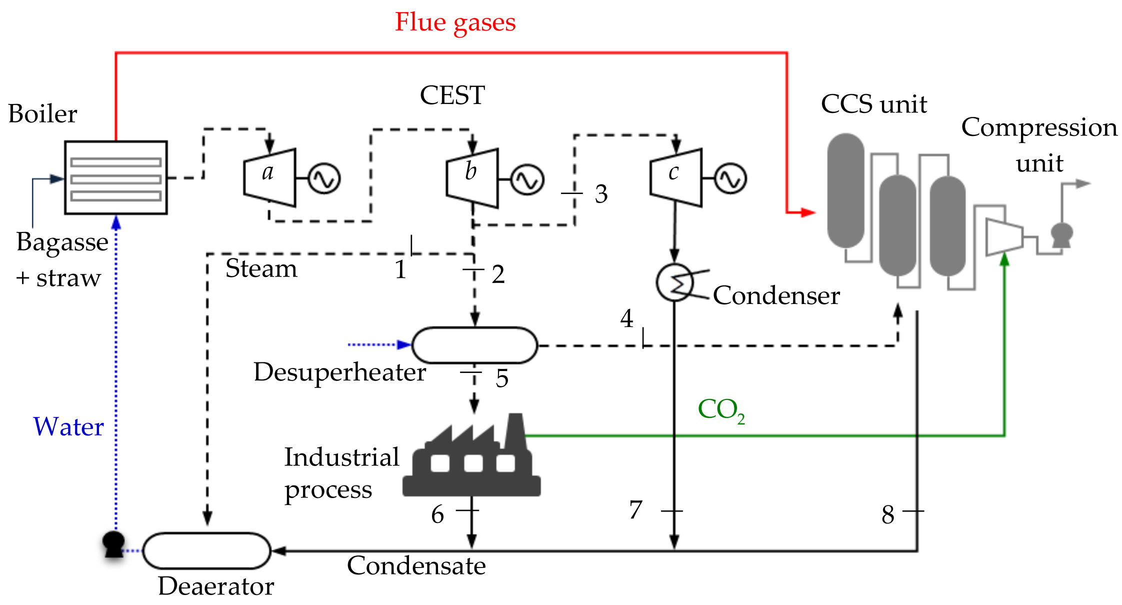

Figure 1.1 BECCS process flow diagram (harvest season).

Figure 1.1 shows the process flow diagram that represents the operation in the harvest season (i.e., with steam extraction for industrial process), with CCS. In software's basic configuration the steam turbine has three bodies. The steam flow to the deaerator (stream 1) corresponds to 2% of the steam raised and is extracted from the turbine body b. The stream (2) feeds the industrial process (stream 5) and the heat exchanger for regenerating the solvent (stream 4), being its thermodynamic state adjusted (in a desuperheater) to the required temperature (137°C). Streams (6), (7) and (8) refer to condensates, being assumed 90% recovery of streams (6) and (8), but both at 90°C; pumps for setting the pressure of condensing flows before the deaerator are omitted in Figure.

Performance results are presented in Table 1.3. In the reference case—cogeneration without CO_2 capture, there is no steam extraction going to the CCS plant and, therefore, power output is maximum. In this case, net power output was estimated at 77 MW during harvest season and 64 MW in the off-season, result that corresponds to a surplus output of 144 kWh per tonne of sugarcane (174 kWh/t generated). Electricity generation, or sold, per tonne of sugarcane crushed is an indicator commonly used to express the efficiency of electricity production in a sugarcane mill, and the result above can be compared to the predicted current best figures in sugarcane sector (130–170 kWh/t of cane) (MOREIRA, J. R. *et al.*, 2016; SEABRA; MACEDO, 2011).

Table 1.3 Performance results for the BECCS systems.

Parameter	Reference Case	Case 1	Case 2	Case 3	Case 4
Energy (as steam) for regeneration (GJ/t CO_2)	-	-	4.4	2.6	1.6
CO_2 emission (Mt CO_2/y)	1.38	1.25	0.58	0.29	0.12
Total CO_2 captured (Mt CO_2/y)	-	0.13 (10%)	0.79 (58%)	1.09 (79%)	1.26 (91%)
Harvest season					
CO_2 captured (combustion) (Mt CO_2/y)	-	-	0.43 (43%)	0.72 (73%)	0.88 (90%)
CO_2 captured (fermentation) (Mt CO_2/y)	-	0.13 (100%)	0.13 (100%)	0.13 (100%)	0.13 (100%)
Net power output (MW)	100.6	100.6	85.3	85.3	88.8
Mill demand (MW)	23.2	23.2	23.2	23.2	23.2
Power requirement for CCS unit (MW)	-	-	11.4	19.3	23.6
Compression power (combustion) (MW)	-	-	7.6	12.9	15.8
Compression power (fermentation) (MW)	-	2.4	2.4	2.4	2.4
Net power output (MW)	77.4	75	40.7	27.5	23.8
Off-season					
CO_2 captured (combustion) (MtCO_2/y)	-	-	0.24 (90%)	0.24 (90%)	0.24 (90%)
Power output (MW)	64.1	64.1	48.8	55.0	58.6
Power requirement for CCS unit (MW)	-	-	12.3	12.3	12.3
Compression power (MW)	-	-	8.2	8.2	8.2
Net power output (MW)	64.1	64.1	28.3	34.5	38.1
General results					
Total electricity output (GWh/y)	695	682	408	356	346
Surplus electricity output (GWh/y)	575	562	288	236	226
Surplus electricity per tonne (kWh/t)	144	141	72	59	57
Energy penalty due CCS	-	2%	43%	50%	52%

Case 1 presents a special case in which capture of only CO_2 from fermentation was considered. As the CO_2 from fermentation is naturally a pure stream, and separation is not necessary, CO_2 goes directly to the compression unit. Power requirement for compression was estimated at 2.4 MW (2% of the net power output) and capture corresponds to 0.13 Mt CO_2/y, which means 10% of the total mill's emissions.

Capturing CO_2 from both fermentation and combustion imposes meaningful energy penalties. There is a constraint in Case 2—with 1998 kg of steam required per tonne of CO_2—due to steam availability: during harvest season the system is unable to supply all required steam for both the industrial process and solvent regeneration, thus forcing the reduction of the capture rate. In all cases a minimum steam flow of 3 kg/s (stream (3)) was assumed to be expanded at *c*. Results of Case 2 indicate that it is possible to capture only 43% of the CO_2 emitted by the combustion process. However, during the off-season, as no steam is required for the industrial process, 90% of the CO_2 from combustion gases is captured (the maximum assumed). Thus, power required for compression during harvest season is due to all CO_2 from fermentation and to the amount captured from flue gases, while during off-season all possible CO_2 captured from flue gases (90%) is compressed. In summary, annual capture rate was estimated at 58%, capturing 0.79 Mt CO_2 (0.13 from fermentation), which is a significant value for a BECCS system, taking into account what has been considered. However, in this case it is predicted a significant reduction in net power output: 48% of the total power during harvest season and 59% otherwise. The balance corresponds to the surplus of 40.7 MW and 28.3 MW, in the harvest and the off-season, respectively. Even though, results still correspond to meaningful surplus electricity regarding the current practices: 72 kWh/t of cane.

In Case 3 the heat requirement for solvent regeneration is 2.6 GJ/t CO_2, and this demand is related to a technology that is expected to be feasible by 2020 (PEETERS; FAAIJ; TURKENBURG, 2007). Current technologies are yet further from this parameter (3.2–3.6 GJ/t CO_2) (HETLAND *et al.*, 2016; VAN DER SPEK; RAMÍREZ; FAAIJ, 2017). With lower steam requirement per tonne of CO_2 captured (1180 kg), capture from combustion would be higher, but the maximum cannot yet be reached: 73% during harvest season. As consequence, total annual capture would be 1.09 Mt CO_2 (capture rate of 79%). The impacts on power would correspond to 68% of the total generation during the harvest season and to 37% during the off-season. Due to the higher power consumption during harvest, final surplus electricity decreases to 59 kWh/t of cane.

Finally, in Case 4, with heat requirement equivalent to 726 kg of steam per tonne of CO_2, it would be possible to supply all steam required both for the industrial process and the CCS unit, resulting in maximum capture efficiency. In this case the annual capture would be 1.26 Mt CO_2, corresponding to a capture rate of 91% (due to fermentation). The net production of energy during the harvest was further reduced (73% of the power output), but the impact during off-season was reduced to 35% of power output. The indicator of surplus electricity per tonne of sugarcane was estimated at 57 kWh.

1.3.2. Economic performance

In order to compare the results presented in this paper with some presented in the literature, the economic assessment was done with all costs estimated for 2014, in Euro. In all cases the investments were supposed to correspond to a single flow in year 0 of the cash flow.

In the reference case, in which the aim is to maximize surplus electricity, the MSP was estimated taking into account all taxes and charges usually incident to this type of enterprise in Brazil. Table 1.4 presents the main costs and the calculated MSP for the reference case.

Table 1.4 Costs and economic performance indicators for the BECCS systems.

Parameter	Reference Case	Case 1	Case 2	Case 3	Case 4
Total plant costs					
Power plant (M€)	77	77	77	77	77
CO_2 capture unit (M€)	-	-	171.6	224.5	253.8
CO_2 compression unit (M€)	-	11.1	26	33.6	37
CO_2 transport and storage (M€)	-	1.3	3.0	4.0	4.5
Fuel costs (M€/y)	11.4	11.4	11.4	11.4	11.4
O&M costs					
Power plant (M€/y)	1.5	1.5	1.5	1.5	1.5
CO_2 capture unit (M€/y)	-	-	10.0	13.1	14.8
CO_2 compression unit (M€/y)	-	0.5	1.2	1.5	1.7
CO_2 transport and storage (k€/y)	-	26	62	80	89
Performance indicators					
Electricity price (MSP) (€/MWh)	48	48	48	48	48
CO_2 credit (minimum price) (€/t CO_2)	-	21	66	62	59

The MSP resulted at 48 €/MWh, a value that could be compared with the reference price set in auctions for new enterprises in 2014 (New Energy Auctions), 62 €/MWh, for biomass power units (CCEE, 2018). The difference is explained by the discount rate usually assumed by investors in bioelectricity (higher than the one assumed here) and by the competition in the electricity sector, which vary depending on the investments in other energy sources and the expectation of investing in new hydro power plants.

Results for the Cases 1–4 are also presented in Table 1.4. The estimated CO_2 credit price, based on the amount of CO_2 captured, would cover all costs (the minimum rate of attractiveness would be 10% per year) and also the loss of revenue due to less electricity sold. In this sense, the results presented in Table 1.4 correspond to the minimum selling price of capturing CO_2.

In Case 1, a small amount of CO_2 is captured with no meaningful energy penalty. The CO_2 minimum credit price was estimated at 21 €/t CO_2, a relative low cost for CCS, being the best opportunity in case of sugarcane mills. The estimated CO_2 price for Case 1 is basically the same presented in (MOREIRA, J. R. *et al.*, 2016) (27.2 US$/t CO_2 in 2014, when the average exchange rate was 1.33 Euro/US$).

It can be seen from Table 1.4 that, in Cases 2 to 4, the capital costs due to the CCS units represent from 72% to 79% of the total investment, and from 88% to 92% of the total annual O&M costs. It is clear from these figures that carbon capture would be the main driver of investments in Cases 2 to 4, far exceeding the costs of surplus electricity production.

A comparison with the results presented by (KHORSHIDI *et al.*, 2016; VAN DER SPEK; RAMÍREZ; FAAIJ, 2017) is shown in Table 1.5. References consider CCS plants based on MEA technology, and both publications were used as reference for estimating costs and performance parameters. However, in both cases the estimates were done for CCS natural gas combined cycle (NGCC) power plants. MEA technology considered in (VAN DER SPEK; RAMÍREZ; FAAIJ, 2017) had a heat specific requirement equal to 3.66 GJ/t CO_2, that would be intermediate between Cases 2 and 3 in this paper, while (KHORSHIDI *et al.*, 2016) considers heat requirement similar to Case 4. As in both references the discount rate is relatively low (7–7.5%), new results related with this study—for a discount rate of 8% per year—were included in Table 1.5. The minimum price to be paid per tonne of CO_2 captured is relatively similar comparing the results of this study (for lower discount rate) to those presented by (KHORSHIDI *et al.*, 2016), but the cases are very different for a straight comparison.

Table 1.5 Comparison among similar cases of CCS in thermal power plants.

Parameter	This Study		(VAN DER SPEK; RAMÍREZ; FAAIJ, 2017)	(KHORSHIDI *et al.*, 2016)
Electricity production technology	CEST		NGCC	NGCC
Power plant capacity (MW)	100		830	557
Specific heat requirement for MEA (GJ/t CO_2)	2.6		3.66	4.4
Total CO_2 captured (Mt CO_2/y)	1.09		1.9	1.31
Discount rate	10%	8%	7.5%	7%
Base year (for costs)	2014		2014	2011
MSP of electricity (€/MWh)	48.0	44.0	90.7	49.4[a]
CO_2 credit (€/t CO_2)	62.0	55.0	80.7	51.1[a]

[a] Original values in US dollar were converted to euro using the average exchange rate in 2011 (0.719).

The more expensive electricity generation is, the higher the credit for capturing CO_2 would be. The results of this study are relative close to those presented by (KHORSHIDI *et al.*, 2016) because here the case is related to a cogeneration unit that mostly uses residual biomass as fuel, despite the fact that the benefits of scaling effects on electricity generation do not exist. The results presented by (VAN DER SPEK; RAMÍREZ; FAAIJ, 2017) are impacted by a higher cost of fuel. Another important aspect is that for the case reported in this paper, the minimum price to be paid for capturing CO_2 is impacted by the stream of CO_2 from fermentation (that varies from 16% of the total in Case 2, to 10% in Case 4) and that has a relatively small cost. Following the same procedure described in this paper, but not considering the capture of CO_2 from fermentation, the credit price would grow from 59 €/t CO_2 to 70 €/t CO_2 (for discount rate 10%). It is also worth mentioning that the amount of CO_2 captured per year is not much smaller (57% to 83%) than in power units that would burn natural gas, despite the much smaller installed electricity capacity (12% to 18%). Comparing biomass and natural gas, the higher carbon content per unit of energy and the much lower efficiency of electricity generation explain the huge penalties of CO_2 capture on electricity generation. Another useful comparison is with the carbon price needed for making a technology competitive. In the case of switching from NGCC to a coal power plant with CCS, considering 8% as the annual capital costs for the investments, (THE WORLD BANK, 2017) presents 85 €/t CO_2 as the break-even price. Thus, in a general sense it can be concluded that the CO_2 capture costs presented in this paper are in line with the estimates presented in the literature, but a main difference is that the BECCS system considered here is able to contribute with negative GHG emissions.

Cases 2 to 4 correspond to different stages of development of MEA based technology. Case 2 corresponds to the current commercial stage, while Case 3 represents the technology that could be available in short term. Moving from current to future technologies would impact carbon capture, with an increase of 38% on annual output as long as Case 3 is compared to Case 2; as previously mentioned, capturing in Case 2 is negatively impacted by the higher steam demand for recovering amine. On the other hand, moving from Case 2 to Case 3 significantly impact surplus electricity, with a decrease of almost 13% in the total electricity that could be sold along the year. The impact on the minimum price to be paid per tonne of CO_2 captured is less pronounced, with a reduction of 6% comparing Cases 3 and 2. The change from Case 3 to Case 4 is less pronounced (an increase of 16% in annual capture, a reduction of 2.8% in surplus electricity, and a 4.8% reduction in carbon costs).

The fact that the minimum price to be paid per tonne of CO_2 captured is almost equal in all three cases indicates that, from an economic point of view, it is not necessary to wait for advanced MEA technologies in order to go for pilot BECCS projects. Therefore, it is necessary to consider technologies that would impact less on surplus electricity. However, a very important find is that CO_2 capture from fermentation has a lower cost and a small impact on the energy balance, and should be prioritized for pilot BECCS units in Brazil.

1.3.3. Scaling effects

For the considered BECCS system, scaling effects are analyzed in this section. Case 3, with heat requirement for solvent regeneration equivalent to 2.6 GJ/t CO_2, was chosen to be scaled into a smaller industry (2 Mt/y) and a larger mill (8 Mt/y). The same performance parameters previously presented were considered, and costs were estimated according to the assumptions mentioned before (for 10% discount rate). Table 1.6 presents total plant costs and the main economic results. Scale effects are clear both on the MSP of surplus electricity and on the minimum price to be paid for capturing CO_2.

Table 1.6 Total investment costs and economic performance results for different milling capacities.

Parameter	Milling Capacity (Mt/y)		
	2	4	8
Performance results			
Power plant capacity (MW)	50	100	200
CO_2 captured (Mt CO_2/y)	0.55	1.09	2.19
Electricity price (MSP) (€/MWh)	54	48	43
CO_2 credit (minimum price) (€/t CO_2)	80	62	48
Total plant costs			
Power plant (M€)	48.5	77.0	122.3
Capture unit (M€)	148.1	224.5	340.3
Compression unit (M€)	22.2	33.6	50.9
Transport and storage (M€)	2.7	4.0	6.1
Economic indicators (as function of annual outputs)			
Investment cost per tonne of CO_2 captured (€/t)	405	310	237
Investment cost per surplus electricity unit (€/MWh)	1874	1435	1099

Taking as reference the price presented by (VAN DER SPEK; RAMÍREZ; FAAIJ, 2017) in the case of capture in a large combined cycle power plant (80.7 €/t CO_2), and assuming that people would be able to pay this value in the future, full carbon capture (both from fermentation and combustion) would be feasible in Brazilian sugarcane mills, but it is clear that the feasibility would be enhanced with the mill capacity. As regard with the results presented by (KHORSHIDI *et al.*, 2016), comparatively the feasibility would exist for larger mills. Considering that mills with capacity equivalent to 2 Mt/y are currently the average in Brazil, in many existing mills it would be feasible to capture CO_2. On the other hand, considering that new mills tend to be larger, in the future it would be reasonable to consider mill's location also taking into account the aim of storing CO_2 at lower costs.

Allocating all capital costs to the annual surplus electricity, the indicator varies from 1874 to 1099 €/MWh, depending on the mill size (see Table 1.6). This figure for the reference case (VAN DER SPEK; RAMÍREZ; FAAIJ, 2017) is only 134 €/MWh. Alternatively, allocating total capital costs to the annual amount of CO_2 captured, this indicator varies from 237 to 405 €/t CO_2 captured per year (Table 1.6), while this figure is 483 €/t in the case presented by (VAN DER SPEK; RAMÍREZ; FAAIJ, 2017). It seems clear that investors should have a completely different rationale in each case: while in case of a natural gas combined power plant CO_2 capture would be a complement that should be fairly paid, in the case of carbon capture in a sugarcane mill surplus electricity produced in a cogeneration unit should no longer be the priority. In this case, the priority should be capturing CO_2, with the advantage that this enterprise would contribute with negative emissions. Indeed, whether the benefits of negative emissions would be recognized, a larger payment per tonne of CO_2 would be possible, and surplus electricity could be more competitive with other generation options.

1.4. Conclusions

This work aimed to explore the technical and economic feasibility of BECCS systems in the Brazilian sugarcane sector. Post-combustion technology based on MEA was considered for capturing CO_2 from biomass combustion, and three technology levels—related to heat requirements for solvent regeneration—were assessed. Results show that CO_2 capture, both from fermentation and combustion, is technically possible but energy penalties are meaningful in case of combustion, with considerable impacts on surplus electricity. Energy penalties due CCS imply deep reduction in electricity generation, varying from 43% to 52% regarding the reference case. In this sense, it is important to evaluate other technologies for capturing CO_2. The more expensive the electricity sold, the higher the price to be paid per tonne of CO_2 captured.

Comparatively, capturing CO_2 from the fermentation is the best opportunity, because of the low impact on the mill, the relatively low cost, and the benefits on the ethanol carbon footprint. Clearly, is the alternative that should be prioritized.

The high impact on electricity production in the case of biomass-based cogeneration units, compared with well-known estimates for natural gas plants, is due to the comparatively low efficiency of electricity generation. Investments and costs are far greater for capturing CO_2 than for generating surplus electricity. In this sense, the rationale for investments should be different: the priority would be capturing CO_2—resulting in net negative emissions, and selling electricity would be a second priority.

The CO_2 credits presented in this document and also in the literature (approximately € 45–80/t CO_2) are much higher than the current price of carbon in different markets (e.g., considering the CO_2 European Emission Allowances, the carbon price was less than € 10/t CO_2 in the first half of 2018 and around € 20/t CO_2 by the end of 2018 (CO2 EUROPEAN EMISSION ALLOWANCES, 2019)), but it is important to take into account some important aspects. First, carbon markets are currently depressed due to low demand. Second, and most importantly, carbon capture and storage would be costly among the mitigation options and the large-scale implementation of CCS systems would be feasible only in the medium to long term.

Supposing that carbon capture through CCS would be a target in the future, investing in a BECCS system in a sugarcane mill would be much more effective than investing in a power plant that burns natural gas, for instance. The price to be paid would be lower, and the result would be negative emissions.

2. BECCS OPPORTUNITIES IN BRAZIL: COMPARISON OF PRE AND POST-COMBUSTION CAPTURE IN A TYPICAL SUGARCANE MILL[1,2]

Abstract

In order to make feasible the efforts that would limit the rise of Earth's temperature to no more than 2°C, profound changes are required in the energy systems. In this sense, BECCS are considered instrumental to attain possible negative emissions. This draws attention to the sugarcane industry in Brazil, where it is possible to produce fuel ethanol at a relative low cost and a large amount of relatively cheap biomass is available. This paper is part of a research that aims to study the combined production of liquid fuels and electricity, using sustainable sources of biomass and maximizing carbon capture. Two cases related to an innovative technology were evaluated and in both the capture is based on amine technology: pre-combustion capture of CO_2 from the fuel gas derived from biomass gasification, and post-combustion capture from gas turbine exhaust gases. Information from the scientific literature was used in modeling the systems, as well as estimating energy penalties and costs associated with capturing, transporting and storing CO_2. The results indicate technical feasibility of both capture options, but difficulties in setting the full integration of the power unit (BIG-CC) with the sugarcane mill and the CCS system, due to the high demand for thermal energy as low-pressure steam. The estimated CO_2 abatement cost is in the range 60–71 €/tCO_2 for pre-combustion capture, and 52–63 €/tCO_2 in the case of post-combustion. Feasibility results are impacted by the scale of CO_2 capture (0.82–1.11 MtCO_2/year), particularly in the pre-combustion case, and the relatively high cost of electricity generation.

Keywords: bioelectricity; bioenergy, biomass-gasification, carbon sequestration, climate change, negative emissions

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[1] The present work is an extension of the work "BECCS Opportunities in Brazil: Pre and Post-Combustion Comparison in a Typical Sugarcane Mill" (2021). Proceedings of the 15th Greenhouse Gas Control Technologies Conference 15-18 March 2021, Available at SSRN: https://ssrn.com/abstract=3811521 or http://dx.doi.org/10.2139/ssrn.3811521

[2] Submitted in the International Journal of Greenhouse Gas Control in June 28th, 2021. Status: under review, updated August 28th, 2022

2.1.Introduction

A profound transformation of energy systems is needed to limit the rise in Earth's temperature to no more than 2°C in this century, or even less (IEA, 2018). In this sense, carbon-neutral energy systems must be available on a large scale in the transition to the second half of this century. There is a wide range of clean energy technologies, some of which are already well established, while others are still under development (IEA, 2020b).

Carbon capture and storage (CCS) is a key driver in putting energy systems on the path of zero net emissions. The process refers to the capture of CO_2 emissions in, for instance, power plants and industrial facilities. Then, CO_2 could be compressed and transported to its injection into deep geological formations (IEA, 2020a). In 2020, International Energy Agency (IEA) (2020a) reported 21 CCS facilities (with no further carbon utilization) with an installed capacity to capture up to 40 $MtCO_2$ each year, and plans for more than 30 additional commercial facilities. Although important incentives have emerged in recent years, clean energy technologies such CCS still need a strong boost if long-term goals are to be achieved.

Bioenergy systems include the use of biomass to generate electricity and heat and produce biofuels. Feedstock could be either forest residues, agricultural and domestic wastes, sewage sludge or dedicated crops. Biomass gasification is a possible intermediate technology to make it suitable for final conversion. The resulting biomass-derived gas (BDG) can be used as fuel in electricity generation, in this case with thermal efficiencies of up to 44% (IEA, 2020c), or in the production of liquid fuels. According to IEA Bioenergy Task 33 (IEA BIOENERGY, 2020), 94 biomass gasification plants, classified with the highest Technology Readiness Level (TRL 9) (i.e., commercial facilities), were operational in 2020. However, none with scale and based on the same technology considered in this work.

BECCS systems (bioenergy systems combined with carbon capture and storage) link two concepts for mitigating greenhouse gas (GHG) emissions: bioenergy and CCS (IEA, 2020a), and are considered a crucial option to achieve possible negative emissions. In BECCS, a negative emission can be obtained when biogenic carbon, removed from the atmosphere with the growth of biomass, is captured after its combustion and stored permanently, as in a geological formation (SANTOS; GONÇALVES; PIRES, 2019). Negative emission is obtained only when the amount of CO_2 captured is greater than the CO_2 emitted throughout the entire BECCS chain, including biomass cultivation (TANZER; RAMIREZ, 2019). The IEA, in its 2DS scenario (i.e., no more than 2°C), has defined that an intermediate target for 2025 is that about 60 $MtCO_2$ is captured in bioenergy systems and stored (IEA, 2017a).There are six

BECCS systems in operation worldwide; one project has been completed and three more are in early development and are expected to be operational by 2025 (GLOBAL CCS INSTITUTE, 2020). Five of these six projects are related to the capture of CO_2 produced during fermentation, in ethanol plants, and only one to the capture of CO_2 in a biomass thermal power plant (660 MW): when completed, the Drax project, in the United Kingdom, will capture 4.3 $MtCO_2$/year (GLOBAL CCS INSTITUTE, 2020). Thus, large demonstration projects are needed for the BECCS technology to advance, but in addition to the intrinsic challenge of deploying CCS technology, large-scale bioenergy systems still need to be realized (IEA, 2017b).

The need to promote BECCS draws attention to the sugar-energy sector in Brazil, in which it is possible to produce fuel ethanol at a relative low cost and with significant reduction in GHG emissions vis-à-vis fossil gasoline (MOREIRA, J. R. *et al.*, 2016). The results related to the avoided emissions could be even improved, with the storage of the CO_2 produced during fermentation (KEMPER, 2015). However, it is possible to go further because the relatively low-cost residual sugarcane biomass (bagasse and straw) has been used in conventional cogeneration systems (based on steam turbines) with significant surplus electricity generation (at least 2-3 times the electricity needed by the industrial process) (RESTREPO-VALENCIA; WALTER, 2019). In Brazil, the availability of sugarcane straw at the mill site is a new issue due to the increase in mechanized harvesting and, with good agricultural practice, it is possible that at least 40-50% of the straw available in the field can be transported to the mill to be used as fuel (LEAL *et al.*, 2013). In addition, compared to the results of conventional cogeneration systems, with not yet commercial BIG-CC systems (integrated biomass gasification to combined cycle) it would be possible to at least double the electricity generation in a sugarcane plant, (DESHMUKH *et al.*, 2013). Therefore, there are even better prospects for the future. adequate porosity and permeability of the rock

Permanent CO_2 storage is considered the most critical step in CCS due to the special conditions needed: large geological formations with depth of over 800 m and, in addition, adequate porosity and permeability of the rock (PAGE *et al.*, 2020). In Brazil, preliminary studies estimated storage capacity at 2,000 gigatonnes of CO_2 in aquifers, petroleum fields and coal seams (GLOBAL CCS INSTITUTE, 2017; ROCKETT *et al.*, 2011). In addition, a publication known as the Brazilian Carbon Capture Atlas identified that one of the most promising formations for geological storage is the sandstones of the Rio Bonito Formation, located in the Paraná Basin (KETZER *et al.*, 2016). A sink-source correspondence was performed based on the location of the existing sugarcane plants with the possible sinks, and results are presented in Figure 2.1. Information on the location and milling capacity of 421 sugarcane industrial plants (CTBE - LABORATÓRIO NACIONAL DE CIÊNCIA E TECNOLOGIA DO BIOETANOL, 2013) were used and correlated with parameters of ten oil wells located in the Paraná Basin (BOCARDI; FERNANDES, LUIZ ALBERTO ROSTIROLLA; APPI, 2018). Correspondence between sinks and sugarcane mills showed that 51% of industrial plants located in the Centre-South of Brazil (where is the bulk of sugarcane industry) are within a radius of 300 km with potential storage points, which means feasibility for transportation (IEAGHG, 2013).

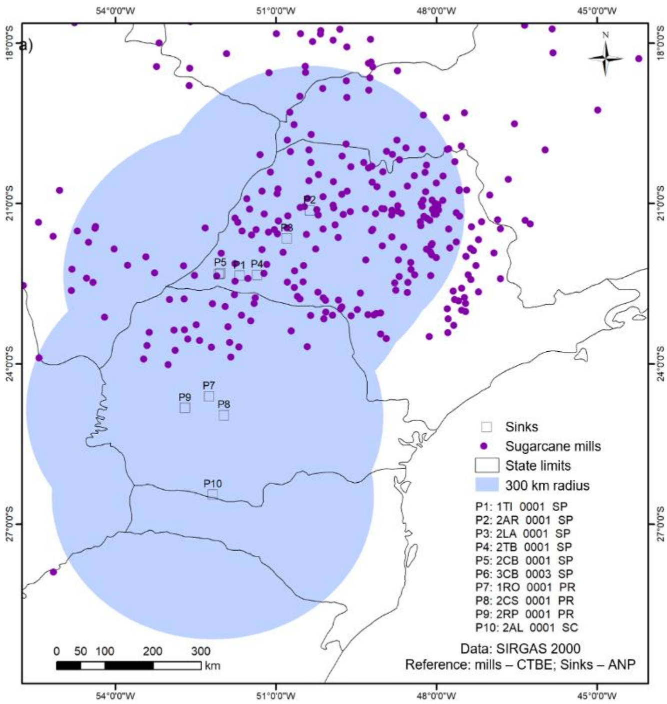

Figure 2.1 Sink-source match for sugarcane mills in Centre-South of Brazil

Pre-combustion capture technology may be a promising option, offering both the possibility of capturing CO_2 at a lower cost and improving the composition of the fuel gas to be burned in the gas turbine (LEUNG; CARAMANNA; MAROTO-VALER, 2014), which motivated the study of the CCS at BIG-CC cycles. On the other hand, the technological challenge would be greater, as two technologies that are not yet fully commercial and therefore expensive, would be combined (IEA, 2020c).

Assessing BECCS opportunities in Brazil is the rationale of an ongoing research focused on combining the production of liquid fuels and electricity, using sustainable sources of biomass and maximizing carbon capture. This paper is the second in a series of studies that assess opportunities for BECCS systems in power units in Brazilian sugarcane mills. In a previous paper the feasibility of a carbon capture unit in a typical sugarcane mill was investigated, integrated to a conventional cogeneration plant, based on condensing-extraction steam turbines – CEST (RESTREPO-VALENCIA; WALTER, 2019). To make the results comparable, some common assumptions were made between the previous paper and this one. At the end, the main results of both papers are compared.

2.2. Materials and methods

In this paper, the adoption of carbon capture in BIG-CC systems integrated to Brazilian sugarcane plants is evaluated. The cases of pre- and post-combustion CO_2 capture were analyzed, and their results were compared with the case of the cogeneration system based on BIG-CC technology, but without CCS. In both cases the capture unit is an amine-based technology, capturing CO_2 right after the gasification, in the pre-combustion case, or from the gas turbine exhaust gases, in the post-combustion one. The technical modelling and economic assessment were based on information from the literature both for the capture technology and for the transport and storage of CO_2.

A typical Brazilian sugarcane mill was considered. These mills are energy self-sufficient and it was assumed that electricity generation would be maximized, with surplus electricity sold to the grid. Internal consumption of electricity per metric tonne of sugarcane was defined as 30 kWh (MOREIRA, J. R. *et al.*, 2016). The power unit must be fully integrated into the plant, and residual biomass – bagasse and straw – was considered available for use as fuel. Bagasse availability is defined by the fiber content of the sugarcane plant (14%), resulting 280 kg of bagasse per metric tonne of cane, with 50% moisture (PEDROSO *et al.*, 2017). On the other hand, the availability of straw in the mill per tonne of sugarcane was considered 50% in relation to the total amount available in the field, resulting in 82 kg per tonne of cane, with 15% moisture (PEDROSO *et al.*, 2017).

The mill's grinding capacity was estimated as the one that allows the best integration from an energy point of view. The plant's industrial operation was estimated to take eight months along the year due to restrictions on sugarcane harvesting, but electricity generation would occur throughout the year. The capacity factor was considered 90% both in the harvest and in off-harvest periods, and it was assumed that sugarcane processing requires steam at 2.5 bar and 137°C. The typical steam demand for the production of sugar and ethanol corresponds to 380–420 kg of steam per metric tonne of processed cane (PEDROSO *et al.*, 2017), but, aware of the restrictions of the BIG-CC systems to meet high demands, it was assumed that the steam demand would be reduced to 280 kg per metric tonne of processed cane, a level that is technically feasible but would require high investment (PINA *et al.*, 2017; SEABRA *et al.*, 2010).

2.2.1. Biomass gasification unit and power system description

The simulation of the gasification process is outside the scope of this study and, in practical terms, the main parameters, including the BDG composition obtained in an oxygen-blown gasifier, were taken from (JIN; LARSON; CELIK, 2009). For the purposes of this work, what is important is the composition and LHV of the BDG, and these results are a function of the biomass composition and the gasifier operating parameters. The biomass in the reference study is switchgrass and here it was assumed that the biomass to be gasified would be bagasse and sugarcane straw. The assumption is that there is sufficient similarity between these biomasses, both physically and chemically. Table 2.1 shows typical results of the ultimate analysis of switchgrass, bagasse and straw.

Table 2.1 Ultimate analysis of the reference biomass (switchgrass) and those assumed in this paper (dry basis)

Weigh % – dry basis	Switchgrass[a]	Bagasse[b]	Straw[b]
Carbon	47.0	46.3	45.0
Oxygen	41.4	43.3	44.0
Hydrogen	5.3	6.4	6.0
Nitrogen	0.5	-	-
Sulphur	0.1	-	-
Ash	5.7	4.0	5.0
Lower heating value (MJ/kg)	17.0	17.5	17.6

[a] (JIN; LARSON; CELIK, 2009); [b] (RODRIGUES; WALTER; FAAIJ, 2007).

Upon leaving the pressurized gasifier, the resulting BDG undergoes cooling and cleaning before feeding the combustion chambers of the gas turbine. BDG is a low calorific (LCV) gas, and its use in commercial gas turbines may imply their operation in off-design conditions (RODRIGUES; FAAIJ; WALTER, 2003). It was assumed that the gas turbine is similar to GT11N2, a turbine that produces 117 MW under ISO conditions. The energy from the exhaust gases is recovered in the heat recovery steam generator (HRSG) and the gas flow is further used to dry the biomass that feeds the gasifier. Here it was assumed that steam is raised in two pressure levels: first at 31.65 bar, to supply a small amount of steam required by the gasifier, and second, at the pressure that allows the maximization of the flow that first expands in the steam turbine, generating power. Gas turbine simulation was performed in a non-commercial software able to deal with gas turbines and derived cycles, developed by the authors. Calibration of the simulation procedure was performed comparing results with GateCycle software version 6.1.4, for further details see RESTREPO-VALENCIA (2018).

As burning LCV gases in the gas turbine implies adjustments in its operation, RODRIGUES, WALTER, & FAAIJ (2003) discussed various strategies. For the purspose of this work, two approaches were considered: de-rating and blast-off air from compressor. De-rating is due to the reduction of firing temperature, and blast-off air means its extraction at the compressor discharge. An air separation unit (ASU) would be integrated with the gas turbine to provide oxygen for the gasifier and, thus, the ASU unit operates with blast-off air.

2.2.2. Capture unit

Ideally, the capture unit would be totally integrated with the power plant and it was assumed 90% as the maximum possible capture efficiency (OREGGIONI *et al.*, 2015). In the case of pre-combustion, the capture takes place after the gasifier, and then the CO_2 flow from the fermentation is added; the mixed flow is sent to the stages of compression, transport and storage. As the CO_2 from fermentation is naturally a pure stream, separation is not necessary. On the other hand, in the case of post-combustion, CO_2 is captured from the exhaust gases of the gas turbine and, as in the previous case, this flow is added to the fermentation flow and sent to the following steps.

The CO_2 flow in the exhaust gases was estimated from the gas turbine simulation, considering the fuel gas composition. For estimating CO_2 from fermentation, it was assumed the most impactful situation: an autonomous distillery, where 100% of sugarcane goes for ethanol production. A typical Brazilian mill with medium-to-large capacity (4 Mt/y) produces both ethanol and sugar with some flexibility (in general, each output varies between 40% and 60%; basis is the sugarcane input) (MACEDO; SEABRA; SILVA, 2008). In this sense, CO_2 from fermentation was calculated for an ethanol production of 86.3 liter per tonne of sugarcane (MACEDO; SEABRA; SILVA, 2008) and a CO_2 production of 0.96 kg per kg of ethanol (MOREIRA, J. R. *et al.*, 2016). This results in an emission index 0.78 kg of CO_2 per liter of ethanol, calculated for an ethanol density of 0.809 kg/L.

For small amounts of CO_2 captured in CCS, as the pre-combustion case suggests, the common practice is the use of physical absorption. However, here for all CCS configurations, capture technology is based on chemical absorption using monoethanolamine (MEA) as solvent. Currently, chemical absorption using amine-based solvents is the most advanced technique for CO_2 separation (TRL 9-11) (IEA, 2020a). The properties of the solvent for the absorption process determine energy penalties. MEA technology parameters were taken from

(PEETERS; FAAIJ; TURKENBURG, 2007), where authors present three stages of technology development. For the purpose of this study, and to keep the basis for comparison with a previous study, the medium-term technology for solvent regeneration was assumed, corresponding to 2.6 GJ/tCO_2 (1,180 kg of steam per tonne of CO_2). Steam at 2.5 bar and 137°C would be used to heat the solvent and its regeneration. For the treatment of the exhaust gases from the gas turbine the energy requirement was estimated from (KHORSHIDI *et al.*, 2016), resulting in 0.258 MJ per kg of exhaust gas. This penalty includes the electricity requirement for pumping and blowing in all main processes and auxiliaries.

2.2.3. CO_2 compressor train

The relevant parameters related to the compression stage were estimated following the model proposed by MCCOLLUM; OGDEN (2006). CO_2 would be compressed from one bar to its critical pressure (73.9 bar), and then, in the liquid phase, a pump would be used to boost final pressure at 150 bar. At this pressure, CO_2 stream can be transported via pipeline. For the first step, CO_2 was assumed as an ideal gas and compression was divided into five stages with intermediate cooling and isentropic efficiency about 85% per stage. In addition, pumping power requirements were estimated assuming isentropic efficiency of 85%.

2.2.4. Transport and storage

CO_2 transport was assumed to be via pipeline to the final location. Conservatively, the length of the pipeline was assumed 100 km, which is considered an adequate distance to explore possible CCS routes and is within the previously presented sink-source assessment considering the alternatives for permanent storage. For the storage location, it was considered the sandstones of the Rio Bonito Formation, in the Paraná Basin.

2.2.5. Pre and post-combustion configuration flowchart

Figure 2.2 and Figure 2.3 represent flowcharts of the BECCS system in the case of pre and post-combustion capture, respectively. As shown in these illustrations, the steam demand due to the capture system is met by a conventional boiler (during the harvest period), burning biomass. As will be explained later, this solution was imposed due to the impossibility of generating so much steam with HRSG alone. In the case of post-combustion, the capture system is located after the biomass dryer.

Code	Equipment
Gasifier island	
A	Biomass preparation
B	Feeder
C	Gasifier
Gas clean up	
D	Syngas cooler
E	Ceramic filter
Air separation unit – ASU	
F	Integrated ASU
G	Oxygen compressor
H	Nitrogen compressor
I	N_2 boost compressor
CCS Unit	
J	Absorber
K	CO_2 compressor
L	Transport and final storage
Gas turbine	
M	Gas turbine
N	HRSG
O	Steam turbines
Mill	
P	Sugarcane processing
Additional steam generation unit	
Q	Additional steam generator

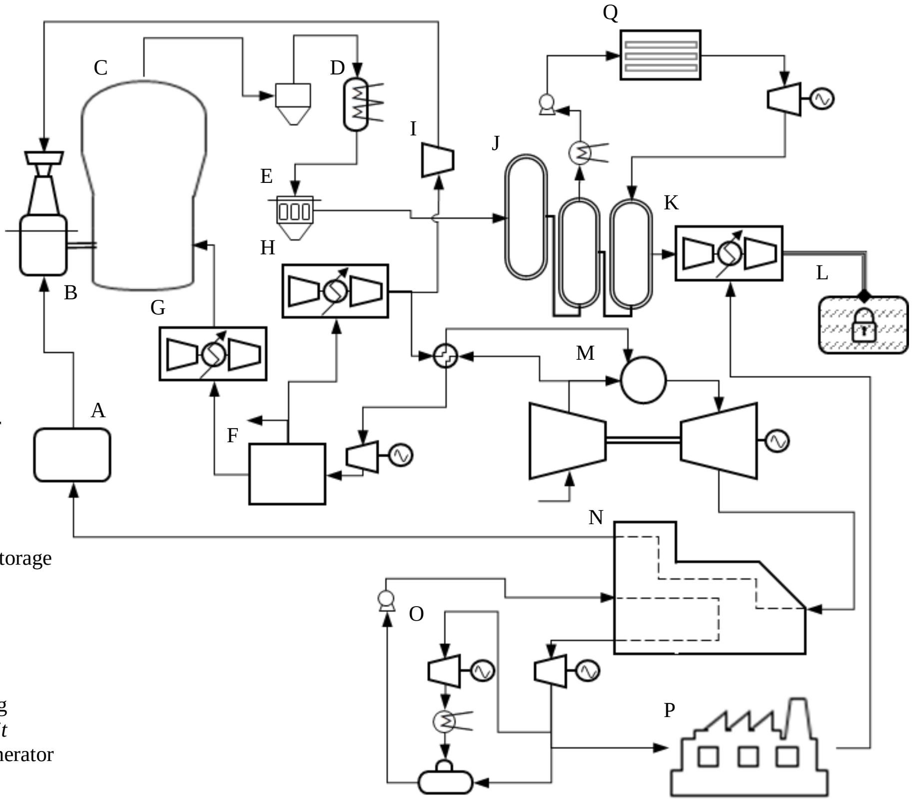

Figure 2.2 Simplified flow diagram of the pre-combustion case

Code	Equipment
Gasifier island	
A	Biomass preparation
B	Feeder
C	Gasifier
Gas clean up	
D	Syngas cooler
E	Ceramic filter
Air separation unit – ASU	
F	Integrated ASU
G	Oxygen compressor
H	Nitrogen compressor
I	N_2 Boost compressor
CCS Unit	
J	Absorber
K	CO_2 Compression
L	Transport and final storage
Gas turbine	
M	Gas turbine
N	HRSG
O	Steam Turbines
Mill	
P	Sugarcane processing
Additional steam generation unit	
Q	Additional steam generator

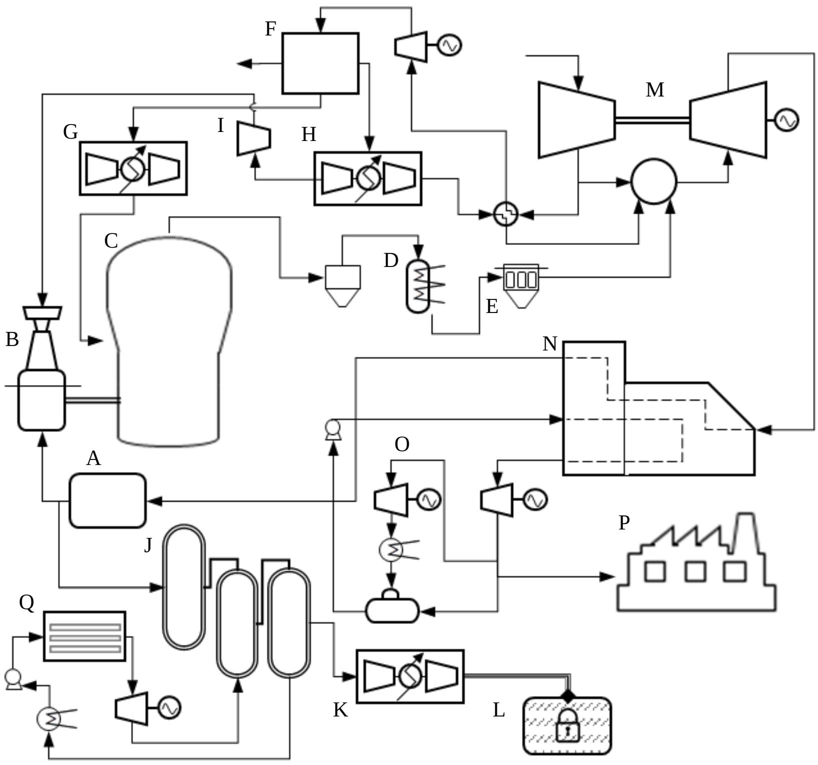

Figure 2.3 Simplified flow diagram of the post-combustion case

2.2.6. Economic performance assessment

The economic assessment was carried out based on information available in the literature. To allow comparison with the results of a previous study (RESTREPO-VALENCIA; WALTER, 2019) (see section 2.4), here location factors were not assumed; the impacts of this simplification are discussed later in this paper. All costs are presented in $€_{2020}$. The considered useful life is 25 years for all equipment and a discount rate of 8% was assumed. As there is significant surplus electricity production in the three cases (two related to CO_2 capture, plus one without capture, for comparison), its minimum selling price (MSP) was considered in the economic assessment. In both cases with CCS, the minimum revenue associated with carbon storage has been estimated and must cover all assumed investments and penalties, including unsold electricity.

For the gasification system, scaling was considered according to Equation (2.1), having as reference the costs presented in JIN; LARSON; CELIK, (2009), which were assumed to be of the n^{th} unit. In the equation, C represents the cost of capital, Q the capacity, α is the scale factor and the subscript zero indicates the case of reference. For the scale factor, a range between 0.50 and 0.77 was used, depending on the component (JIN; LARSON; CELIK, 2009). Three main subunits were considered in the gasification area: gasifier island (feed preparation, pressurized O_2 gasifier, ash cyclone and N_2 boost compressor), gas clean-up (BDG cooler and ceramic filter), and ASU (integrated ASU, O_2 compressor and N_2 compressor).

$$C=C_0\cdot\left(\frac{Q}{Q_0}\right)^{\alpha} \tag{2.1}$$

For the power unit, the turn-key price of a gas turbine equivalent to GT11N2 (i.e., same capacity – 117 MW – and same net thermal efficiency – 34%) was estimated based on a procedure that took into account quotations for different years (PEQUOT PUBLISHING INC, 2003, 2009, 2012, 2013, 2017) the estimate for 2020 is the result of an adjusted function, in US dollars, and finally the value was converted to the currency of this study. In the case of HRSG, heat exchangers and steam turbines, the cost of capital was taken from (JIN; LARSON; CELIK, 2009) and scaled. Finally, for the CCS process, capture and compression costs were estimated from (VAN DER SPEK; RAMÍREZ; FAAIJ, 2017), with 0.6 scaling factor.

2.2.6.1. Fuel costs

Here, biomass is bagasse and straw from sugarcane. The bagasse corresponds to the plant's fiber and, simply put, it was considered zero cost in the plant. Eventually, there is an opportunity cost of selling the surplus to other consumers, but currently this value is very low.

For straw, the estimated cost combines harvest/collecting and transport to the mill, and the resulting value is € 17 per metric tonne of straw (CARDOSO, 2014).

2.2.6.2. Operation and maintenance costs

Operation and maintenance costs (O&M) were estimated, on annual basis, as function of the total investment. For the gasification unit, the used value agrees with (JIN; LARSON; CELIK, 2009). In the case of the power unit, values were based on practices in Brazil for gas turbine operation (WALTER; LLAGOSTERA, 2007). O&M costs for the capture unit and CO_2 compression train were based on VAN DER SPEK; RAMÍREZ; FAAIJ (2017). Table 2.2 summaries the assumptions for O&M.

Table 2.2 Assumptions for operation and maintenance costs

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 (DOE/NETL, 2019)

For transport and storage, the guidelines based on NETL studies (DOE/NETL, 2019) were followed to define annual costs. In the case of transport, the cost per tonne of CO_2 was calculated from the spreadsheet provided in reference, with modifications of the input parameters to maintain coherence with this study (e.g. discount rate, tax rate, equity). Given the lack of specific information on geological formations in Brazil, which would make it possible to make a parallel with the information available in the reference, the range of storage costs presented by NETL was directly assumed: 7 to 18 € per metric tonne of CO_2. The costs for transport and storage reflect overall expenses, i.e., infrastructure, installation, maintenance and operation.

2.2.7. Comparison with conventional cogeneration plant

Aiming to evaluate if BIG-CC technology would be a good option, the results of this study were compared with those for the conventional cogeneration CEST technology presented in a previous paper (RESTREPO-VALENCIA; WALTER, 2019). Modeling hypothesis are basically the same and economic data were updated to set the equivalence with the values presented here. Whenever the case, original values in Brazilian currency (R$) were converted to Euro using the average exchange rate in 2020 (6.15 R$/€). The conventional cogeneration case considers a sugarcane mill with 4.0 Mt/y (million metric tonnes of sugarcane crushed per year) and the steam turbine has one controlled extraction at 2.5 bar and condensation of the remaining flow. In this case, the steam demand of the industrial process was assumed 340 kg of steam per tonne of sugarcane. It was considered that steam is produced at a thermodynamic state that is the state-of-art in Brazilian sugarcane mills (120 bar/535°C). Previous results for CO_2 transport and storage were recalculated according to section 2.2.6.2.

2.3.Results

This section is divided into technical and economic performance of integrated BECCS systems to a typical sugarcane mill. Supplementary material (RESTREPO-VALENCIA; WALTER, 2021), also available at APPENDIX A, presents detailed information on the procedures adopted to define and assess the integration of the CCS to a sugarcane mill.

2.3.1. Technical performance

It was assumed that in all three cases the gas turbine of the BIG-CC system operates at full load and that the operating conditions of the gasifier are constant; the BDG outlet pressure is 28.82 bar. Table 2.3 shows the estimated clean BDG composition. In the case of pre-combustion capture, it is assumed that 90% of the CO_2 flow in the BDG is captured, changing its composition and allowing an increase in its LHV (about 68% in relation to the reference case). As a result, the operating conditions of the gas turbine with low calorific fuel burning improve, and its performance is closer to when natural gas is burned (LEUNG; CARAMANNA; MAROTO-VALER, 2014). Due to the differences in the need for steam, the operation of the system changes significantly from harvest to off-harvest season.

The de-rating of the gas turbine (i.e., reduction of the firing temperature) and the blast-off of the compressor were the strategies adopted to make possible its continuous operation with BDG fuel. The estimated firing temperature of GT11N2 at full load is 1191°C. De-rating and blast-off were imposed according to the authors' judgment, in the search for a compromise solution that would not impose an overload on the compressor, a significant reduction in electrical power and an impact on the steam generation capacity. In fact, as the gasifier operation is the same in all three cases, blast-off is almost equal among them (see Table 2.3). The blast-off airflow (35–36 kg/s extracted from compressor) was imposed by the requirement of oxygen to be produced in the ASU. Thus, in practice only de-rating was controlled and, doing this, what has been checked was the range of the compressor pressure ratios (COHEN; ROGERS; SARAVANAMUTTOO, 1996), which was kept with a maximum 10% variation in comparison with the nominal value at ISO conditions (15.03). In the case of pre-combustion CO_2 capture, with the increase in the fuel LHV and the imposed air blast-off, it was not necessary to impose gas turbine de-rating; in fact, the compressor pressure ratio is even below its operation under ISO conditions (14.7 versus 15.03). With de-rating and changes in compressor pressure ratio, the exhaust gas temperature changes concerning the estimated value at ISO basis, when natural gas is burned (531°C). For further details of gas turbine simulation see supplementary material (Table A-1), in which results of its operation with natural gas and LCV gases are presented (RESTREPO-VALENCIA; WALTER, 2021).

Table 2.3 Estimated results of gas turbine and combined cycle operation

Parameter	Reference case		BIG-CC + Pre-combustion CCS		BIG-CC + Post-combustion CCS	
	Harvest season	Out of season	Harvest season	Out of season	Harvest season	Out of season
BDG composition – gas turbine fuel (mol. %)						
H_2	20.3		25.6		20.3	
CH_4	8.1		10.2		8.1	
CO	15		18.9		15	
CO_2	23.1		2.9		23.1	
N_2	4.7		5.9		4.7	
Ar	0.4		0.5		0.4	
H_2O	28.1		35.5		28.1	
Others	0.3		0.4		0.3	
LHV (MJ/kg)	7.1		11.9		7.1	
Gas turbine						
Blast-off (kg/s)	35.42		36.33		35.42	
De-rating (°C)	37		-		37	
Compressor pressure ratio	15.5		14.7		15.5	
Combustion temperature (°C)	1154		1191		1154	
Exhaust temperature (°C)	516		539		516	
HRSG + Steam turbine						
Steam raised pressure – 1p (bar)	31.65		31.65		31.65	
Steam raised pressure – 2p (bar)	20		25		20	
Steam raised temperature – 2p (°C)	350	350	380	480	350	350
Additional conventional steam generator						
Steam raised pressure (bar)	-	-	20	-	20	-
Steam raised temperature (°C)	-	-	310	-	310	-

1p: first pressure level; 2p: second pressure level

As mentioned, the demand for low-pressure steam in a sugarcane mill is high, and the steam requirement is further increased by installing the CCS system; consequently, thermal integration is a challenge. In view of the objectives, maximizing CO_2 capture was defined as the main priority. Even with the reduction in steam demand to 280 kg/t of cane, it was not possible to find a solution that corresponded to the ideal thermal integration. To increase steam generation, at the HRSG the pinch-point and approaching temperatures were reduced to the limits. In the end, as it was not possible to meet steam demands only with the HRSG, in the cases in which CO_2 capture is considered the inclusion of a conventional steam generator (thermal efficiency 85%), operating only during the harvest, was assumed. It was assumed that there is no capture of CO_2 from the exhaust gases of this steam generator.

In addition, to increase steam generation it was assumed that the temperature of the steam generated in the HRSG can be reduced in the post-combustion case (see Table 2.3). In the off-harvest season, with lower steam demand, a supposed increase in steam temperature aims to maximize electricity generation.

Results of the two BECCS systems, considering the integration of BIG-CC and CCS to a typical sugarcane mill, are presented in Table 2.4. Mill capacity indicates the minimum industrial size to enable integration, as estimated; in a smaller plant, the availability of biomass would not be enough. The average milling capacity in Brazil is slightly larger than 2 Mt/y (MOREIRA, J. R. *et al.*, 2016); currently there are 46 units with equal or larger capacity than 4 Mt/y, and 11 equal or larger than 6 Mt/y— with larger plants the general trend in the future.

Results of CO_2 capture are also presented in Table 2.4. The results of CO_2 production, absolute capture and the percentage of CO_2 captured are different between the two cases also because the mills are different in capacities. In both cases, all the CO_2 produced during the fermentation is captured, but the absolute amounts differ due to the different industrial capacities. As a simplifying hypothesis, all the CO_2 emitted due to burning biomass in the conventional steam generator goes to the atmosphere, and mainly in the post-combustion case this flow is significant. Also by hypothesis, 90% of the CO_2 in the processed flows is captured. Comparing both cases, a disadvantage of the pre-combustion one is that all CO_2 generated in the gas turbine goes into the atmosphere. As consequence, in the pre-combustion case only 46% of the CO_2 produced in the industrial process is captured, while this value rises to 68% in the post-combustion one. The absolute amount of CO_2 captured is 76% higher in the post-combustion case, but the mills have different capacities.

Table 2.4 Performance results for the reference case and two BECCS systems

Parameter	Reference case		BIG-CC + Pre-combustion CCS		BIG-CC + Post-combustion CCS	
	Harvest season	Out of season	Harvest season	Out of season	Harvest season	Out of season
Mill capacity (Mt/y)	3.3		4.2		4.9	
Power consumption						
ASU power[a] (MW)	-1.58		-1.37		-1.58	
O_2 compressor power (MW)	2.62		2.68		2.62	
N_2 compressor power (MW)	4.31		4.24		4.31	
N_2 boost compressor power (MW)	0.25		0.28		0.25	
Fuel handling	0.32		0.33		0.32	
Lock hopper/feeder	0.23		0.24		0.23	
Flow gases treatment – CCS unit (MW)	-		1.22		9.95	
CO_2 compressor (MW)	-	-	11.00	6.34	18.94	13.08
Power output						
Gas turbine net power (MW)	117	117	112	112	117	117
Steam turbine (combined cycle) net power (MW)	20	40	22	35	20	20
Additional steam turbine (steam generator) power (MW)	-	-	11	-	21	-
Gross net power output (MW)	131	151	126	133	123	107
Surplus electricity per tonne of sugarcane (kWh/t)	298		211		159	
Net thermal efficiency	37%		27%		21%	
CO_2 sources						
CO_2 production in biomass gasification[b] (Mt/y)	-		0.54		-	
CO_2 production at gas turbine (combustion) (Mt/y)	1.24		0.67		1.24	
CO_2 production during fermentation (Mt/y)	0.22		0.28		0.33	
CO_2 production in a conventional steam generator (Mt/y)	-		0.28		0.55	
Total CO_2 production ($MtCO_2$/y)	1.46		1.77		2.12	
CCS						
CO_2 captured ($MtCO_2$/y)	-		0.82		1.44	
Fraction of CO_2 captured	-		46%		68%	
Emission ($MtCO_2$/y)	1.46		0.95		0.67	

[a] In the assumed integrated ASU/gas turbine system, air is compressed in the gas turbine compressor (at 15.7 bar for the reference and post-combustion cases, and 14.9 bar for the pre-combustion case) and, subsequently, an air expander is added upstream to the ASU to recover some power (as electricity) while reducing the air pressure to the level needed (11 bar).

[b] In the reference and post-combustion cases, the CO_2 produced during gasification is added to the flow produced in the gas turbine combustion chamber.

2.3.2. Economic performance

The economic assessment was carried out with all costs estimated for 2020, in Euro, and in all cases the investments correspond to a single flow in year 0 of the cash flow. Table 2.5 presents the main costs and economic results for all three cases assessed.

Table 2.5.Cost and economic results for BECCS systems

Parameter	Reference case	BIG-CC + Pre-combustion CCS	BIG-CC + Post-combustion CCS
Total plant costs			
Gasifier island (M€)	43	44	43
Gas clean-up (M€)	48	49	48
ASU (M€)	24	25	24
Capture unit (M€)	-	156	241
Compression train (M€)	-	30	41
Gas turbine (M€)	31	31	31
HRSG and heat exchangers (M€)	27	27	27
Steam turbine (M€)	27	24	17
Additional steam turbine cycle (M€)	-	14	22
Fuel costs (M€/y)	5	6	7
O&M costs			
Gasification (M€/y)	5	5	5
Power plant (M€/y)	2	2	2
Capture unit (M€/y)	-	9	14
Compression unit (M€/y)	-	1	2
Transport (M€/y)	-	5	6
Storage (M€/y)	-	6 – 15	10 – 25
Performance indicators			
Electricity price (MSP) (€/MWh)	40	40	40
CO_2 abatement cost (€/tCO_2)	-	60 – 71	52 – 63

The minimum selling price (MSP) of surplus electricity was estimated for the reference case (BIG-CC without CCS), taking into account all taxes and fees normally applicable to this type of investment in Brazil. For the cases considering CCS, the estimated cost of CO_2 capture should cover all costs besides the loss of revenue due to less electricity sold. In this sense, the results presented correspond to the minimum selling price of CO_2 capture service, assuming the discount rate of 8% per year.

2.3.3. Conventional cogeneration plant

In order to be more assertive about the potential feasibility of BIG-CC systems with CCS, the results obtained in this study were compared with those of a conventional CEST power system integrated with a sugarcane mill, also considering capture; for details see (RESTREPO-VALENCIA; WALTER, 2019). Table 2.6 presents the performance results. The hypotheses for solvent regeneration, CO_2 transport and storage are equal to those assumed here.

Also in this case it was observed that during the harvest season the system would not be able to supply all the steam necessary for the industrial process and solvent regeneration and, therefore, it was necessary to reduce the capture rate. The CO_2 capture from combustion reached 73% during harvest season and the maximum of 90% in off-harvest. As consequence, total annual capture would be 1.09 $MtCO_2$ (global capture rate of 79%).

Table 2.6 Performance results for the BECCS system based on conventional CEST technology (RESTREPO-VALENCIA; WALTER, 2019)

Parameter	Harvest season	Out of season
Mill capacity (Mt/y)	4.0	
Net power output (MW)	85.3	55.0
Mill demand (MW)	23.1	-
Flow gases treatment – CCS unit (MW)	19.3	12.3
CO_2 compressor (MW)	15.3	8.2
Gross net power output (MW)	27.6	34.5
Surplus electricity per tonne of sugarcane (kWh/t)	59	
CO_2 production (combustion) (Mt/y)	1.25	
CO_2 production during fermentation (Mt/y)	0.13	
CO_2 captured ($MtCO_2$/y)	1.09	
Fraction of CO_2 captured	79%	
Emission ($MtCO_2$/y)	0.29	

Table 2.7 presents the main costs and the calculated MSP for the CEST case.

Table 2.7. Cost and economic results for BECCS systems based on conventional CEST technology

Parameter	Value
Total plant costs	
Power plant (M€)	59
Capture unit (M€)	239
Compression train (M€)	36
Fuel costs (M€/y)	10
O&M costs	
Power plant (M€/y)	1
Capture unit (M€/y)	14
Compression unit (M€/y)	2
Transport (M€/y)	6
Storage (M€/y)	8 – 19
Performance indicators	
Electricity price (MSP) (€/MWh)	40
CO_2 abatement cost (€/tCO_2)	67 – 78

2.4.Discussion

In the case without CCS and in the post-combustion case, the results of gas turbine power output are almost the same as for the operation with natural gas and, for the pre-combustion case, there is a slight reduction (4%). The penalties imposed by gasification and CCS impact the gross net power. For pre-combustion capture, CCS penalties are minimized in comparison to post-combustion: they are 8.8 times smaller for gas processing (due to the significant volume reduction in the flow treated), and 1.7 times smaller for CO_2 compression (due to the lower capture).

For the case BIG-CC without CCS, net electricity output is 130 MW during harvest season and 151 MW otherwise, being the difference explained by the steam demand of ethanol production. In pre- and post-combustion cases, gross net power output is affected both by the higher steam demand (mainly) and the CCS power penalties. Compared with the case without CCS, in the pre-combustion case gross net power is reduced 3% during harvest season and 12% otherwise; one reason is that the partial removal of CO_2 from the BDG changes fuel composition, and then, there is a reduction of the mass flow in the expansion, in the gas turbine, affecting power generation (SUDIPTA; JANA, 2014). Higher impacts are observed in the post-combustion case, with a 6% reduction of net power output during harvest season, and 29% in the off-harvest season. Post-combustion capture implies a higher steam demand for amine regeneration, and this mostly explains the impacts on power performance (KHORSHIDI *et al.*, 2016).

Surplus electricity per metric tonne of sugarcane processed is a common indicator used to express efficiency of electricity generation in the sugarcane sector, with the best figures in the range 75—130 kWh/t (MOREIRA, J. R. *et al.*, 2016; SEABRA; MACEDO, 2011; SOUZA, S. P.; GOPAL; SEABRA, 2015). Results for the case without CCS correspond to a production of surplus electricity of 298 kWh/t. With CCS, surplus electricity would be significantly affected, with a 29% reduction in the case of pre-combustion capture and 47% in the post-combustion case. In the case of post-combustion capture, 158 kWh/t means a drastic reduction in surplus electricity, but it is even higher than the best results that can be achieved with conventional cogeneration systems (see Table 2.8). From a technical point of view and prioritizing the generation of surplus electricity, the best alternative is pre-combustion capture.

Table 2.8 Comparison among BECCS cases

Parameter	This study		Adapted from (RESTREPO-VALENCIA; WALTER, 2019)
Electricity production technology	BIG-CC	BIG-CC	CEST
Power plant installed capacity (MW)	162	157	100
Surplus electricity per tonne of sugarcane (kWh/t)	211	158	59
Capture technology	Pre-combustion	Post-combustion	Post-combustion
Total CO_2 captured ($MtCO_2$/y)	0.82	1.44	1.09
Electricity price (MSP) (€/MWh)	40	40	40
CO_2 abatement cost	60 – 71	52 – 63	67 – 77

The MSP was estimated at 40 €/MWh, which shows good agreement with the prices set in the last auctions held in Brazil (CCEE, 2020). From Table 2.7, it can be seen that MSP of electricity for the conventional case (CEST) is also 40 €/MWh; one would expect the cost of CEST systems to be lower (PELLEGRINI; DE OLIVEIRA JÚNIOR; BURBANO, 2010), but it is important to note that the costs of the n^{th} BIG-CC plant were considered here. In fact, the investment cost for CEST technology is much lower than for BIG-CC (about 550 €/kW versus 1299 €/kW), but the former is proportionally much more impacted by energy penalties. Furthermore, this single comparison is unfair, because CEST is a mature technology. It is also important to mention that the discount rate assumed by investors in bioelectricity in Brazil is usually higher than the one assumed here – 12%, instead 8% (SEABRA *et al.*, 2010); for the 12% discount rate, MSP goes even higher: 51 €/MWh for BIG-CC technology and 45 €/MWh for CEST.

Capital costs due to CCS are significant on total investments: from Table 2.5 it can be seen that them represent 45% to 56%, in the pre- and post-combustion cases, respectively. For the CEST case, the capital cost of capture and compression stages represent 83% of capital costs. The annual O&M costs associated with the CCS represent 71% of the total costs, the main portion being transportation: 22% of the annual O&M cost for post-combustion systems, and 33% for pre-combustion. Storage costs represent an uncertainty in the estimate due to the lack of information on geological formations in Brazil. Here it is important to note that as location factors were not considered, the estimated CO_2 abatement costs are an underestimate. In association with the simplification made, as a CEST system has few imported equipment, there would be an additional economic advantage for this technology.

Comparing the estimated costs of CO_2 capture, for the post-combustion system the costs would be in the range 52–63 €/tCO_2, while for the pre-combustion system the estimated costs would be between 67 and 77 €/tCO_2. These results are impacted by the scale effect in the capture, which is smaller in the pre-combustion case. In addition, the more expensive the generation of electricity, the higher the cost of capturing CO_2, but here the electricity costs are basically the same for CEST and BIG-CC options. The estimated costs of CO_2 capture for the CEST-based system are in the range 67–78 €/tCO_2, higher than for the BIG-CC based cases. However, as the BIG-CC technology is still far from the commercial stage, and considering that strictly speaking there would be additional economic disadvantages for it, it seems clear that all medium-term policies to promote BECCS must be based on CEST technology.

In the literature, the estimated cost of CO_2 capture for MEA technology in post-combustion systems is presented in the range 38–86 €/tCO_2 (KHORSHIDI *et al.*, 2016; VAN DER SPEK; RAMÍREZ; FAAIJ, 2017), but these estimates are for larger plants, in general powered by natural gas. For pre-combustion cases, also based on MEA, the estimated reported costs are lower, in the range of 25–68 €/tCO_2 (IEAGHG, 2018; LEUNG; CARAMANNA; MAROTO-VALER, 2014). The comparison with the results of this study indicates that the capture of CO_2 in sugarcane plants can be a promising alternative vis-à-vis carbon abatement in power plants in the case of post-combustion systems, but the pre-combustion case explored here is probably of very small capacity. In the case of BECCS, CONSOLI (2019) states that there is no accurate estimate of the cost of capturing CO_2, as it depends on the process and the scale. For example, the author presented a range of 79–257 €/tCO_2 for combustion, while the capture cost in the case of biomass gasification would be 27–68 €/tCO_2.

The IEAGHG (2018) estimated that CO_2 capture costs should be around 35 €/tCO_2 in the coming years. Thus, rigorously only the capture of CO_2 from fermentation in ethanol production would be competitive, since these costs under Brazilian conditions would be lower (MOREIRA, J. R. *et al.*, 2016; RESTREPO-VALENCIA; WALTER, 2019). However, in relation to the results presented here, it should be considered that the effects of learning on capture have not been fully explored. For instance, it is estimated that by 2030 the capital costs in CCS could be reduced by 30%–50% (POUR, 2019).

2.5. Conclusions

This paper presents the technical-economic results of the assessment of a BECCS integrated with a sugarcane mill, considering electricity generation based on a BIG-CC system. Pressurized gasification of bagasse and straw – both residual sugarcane biomasses – was considered. The CO_2 capture from gasification/combustion gases was evaluated for MEA technology, for two routes: pre- and post-combustion. In both cases, it was considered that CO_2 from fermentation (ethanol process) is captured as well. It was not possible to achieve the ideal systems integration of the systems due to the high demands on low pressure steam, both for the industrial process and for the capture system.

Under the conditions analyzed, and comparatively, the capture of CO_2 in the pre-combustion route has a smaller impact on the sale of surplus electricity, and the system has higher thermal efficiency, but the capture is lower (0.82 versus 1.44 $MtCO_2$/year). The smaller scale of CO_2 capture from biomass gasification negatively impacts costs. The estimated costs of capture are in the 52–63 €/tCO_2 range in post-combustion case, and in 67–77 €/tCO_2 range in the pre-combustion one. These costs are also impacted by the relatively high cost of electricity generation. The investments and O&M costs associated with capturing are higher than those of electricity generation, which would require the redefinition of priorities by the entrepreneurs.

The costs for post-combustion systems presented in this study are in line with what is presented in the literature, but are higher for pre-combustion capture technology. This is due to the capture scale. Also because of the scale effects, simple comparison with estimates for larger power plants, which burn fossil fuels, is inadequate.

The costs in both reported cases are high when compared to the current carbon price (e.g. under the CO_2 European Emission Allowances the carbon price was 26 €/tCO_2 in 2020 (CO2 EUROPEAN EMISSION ALLOWANCES, 2019)) and even with the estimates for 2030 prices, which should be up to 35 €/tCO_2. Compared to these values, CCS of CO_2 from fermentation would be viable, but not from bioelectricity. However, in the coming decades negative emissions from electricity generation will be necessary to compensate for the remaining fossil-based thermal systems and, in this sense, it will be essential to have bioenergy systems based on sustainable and low-cost biomass, in sites where capturing is possible.

Finally, it is worth mentioning that the current technological status of BIG-CC systems implies that the case reported here could only be considered within many years. For pilot and demonstration BECCS units, what should be explored is the case reported in (RESTREPO-VALENCIA; WALTER, 2019), in which cogeneration systems are conventional (CEST technology).

3. CO_2 CAPTURE IN A THERMOELECTRIC PLANT USING SUGARCANE RESIDUAL BIOMASS[1]

Abstract

The current pursuit for decarbonization is directly related to an ambitious target for keeping warming well below 2°C this century. In the case of electricity generation, the target is to attain net-zero CO_2 emissions by 2050, and bioenergy with carbon capture and storage (BECCS), is the only alternative capable of enabling zero or even negative CO_2 emission. BECCS draws attention to the Brazilian sugarcane sector, where it is possible to combine fuel and electricity production from renewable biomass and integrate it with carbon capture and storage (CCS) of the CO_2 emitted when biomass is converted. This paper is the final part of a research that aims to study CCS in systems of combined liquid fuels production and electricity, using biomass that is already widely available. The assessment presents the BECCS technology in a thermoelectric plant that would use residual sugarcane biomass. Two power technologies were considered: steam cycle based on condensing-extraction steam turbine (CEST) and the integrated biomass gasification to combined cycle (BIG-CC). It contains three main evaluations: the comparison with results from previous studies, the analysis of the impact of the cost of biomass, and finally, the analysis of scale effects. The results fort thermoelectricity indicate capture costs are not higher, and may be 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. In the best cases for thermoelectricity capture abatement cost could be reduced to 54 – 65 € per tonne of CO_2 for the CEST technology, and 57 – 68 € per tonne of CO_2 for the BIG-CC technology.

Keywords: BECCS, bioelectricity, carbon capture and storage – CCS, carbon sequestration, climate change, negative emissions

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[1] Pre-print version intended to be submitted in Applied Energy journal

3.1.Introduction

The last report from the Intergovernmental Panel on Climate Change (IPCC) (2021) confirmed alarming levels of greenhouse gases (GHG) in the atmosphere, concluding that climate change is already affecting all regions of the planet and that continued GHG emissions will cause global warming and irreversible changes in the main components of the climate system.

The Paris Agreement, adopted in 2015, was hailed as a watershed for climate action in international policy. The Agreement builds on commitments to nationally determined contributions (NDCs) to a consistent global response to climate change, with the goal of keeping warming well below 2°C this century. In fact, the long-term goal is to keep warming 1.5°C (KRIEGLER *et al.*, 2018). Following the NDCs, many countries are including in their long-term climate strategies the use of carbon capture and storage (CCS) technologies to reduce emissions from the energy and industrial sectors, highlighting the role of CCS in decarbonization targets (TURAN *et al.*, 2021).

In this sense , global emissions of GHG need to reach net zero by 2050, which requires the contribution of significant negative emissions to offset the remaining ones (SANTOS; GONÇALVES; PIRES, 2019; TANZER; RAMIREZ, 2019). Reduction of GHG emissions includes a huge portfolio of alternatives characterized by energy-sector reductions, such as decarbonization of electricity and fuels, deep reductions in agricultural emissions, and carbon removal with carbon storage on land or sequestration in geological reservoirs (ROGELJ *et al.*, 2018). In the case of electricity generation, the target is to attain net-zero CO_2 emissions by 2050, and bioenergy with carbon capture and storage (BECCS), is the only alternative capable of enabling zero or even negative CO_2 emission.

BECCS technology involves the capture and permanent storage of carbon dioxide from processes where biomass is used for energy purposes (CONSOLI, 2019). Biomass-to-energy in a power unit or a biofuel facility, together with CCS, are two BECCS options. Biomass use for electricity and heat generation is already a commercial option, being the feedstock crop-based biomass, agricultural residues, forest residues or sewage sludge. (KEMPER, 2017). The most recent goal for BECCS, proposed by the International Energy Agency (IEA) (2022), is that almost 3000 $MtCO_2$ must be annually captured by 2070, being the current installed capacity only around 1 $MtCO_2$ per year.

The sugarcane sector in Brazil has a high BECCS potential due to a large amount of available biomass. Brazil is responsible for 27% of the global production of ethanol

(RENEWABLE FUELS ASSOCIATION, 2022), which is the most consumed biofuel in the world. Brazil currently has about operating 360 mills (WALTER *et al.*, 2021), emitting million tonnes of CO_2 per year from both fermentation and biomass burning in the cogeneration processes. MOREIRA, J. R. *et al* (2016), figure a potential of 28 $MtCO_2$ removed per year through CCS only accounting for the CO_2 from ethanol fermentation at mills. In the case of cogeneration, the 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 Brazil's potential for BECCS.

In the sugar-energy sector, bagasse and straw can be stored for use as fuel throughout the year, which benefits the plant's capacity factor. The traditional use of bagasse has provided self-energy sufficiency to the mills. The use of straw is a new issue due to the transition from manual to mechanical harvesting, and its most evident use is also in the generation of electricity, which has the benefit of increasing the surplus (SAMPAIO *et al.*, 2019). The amount of straw that can be recovered from the field must consider agronomic effects and depend especially on climate and soil conditions (HERNANDES; LEAL, 2020).

Given the importance of BECCS technology to achieve global goals and the potential for sustainable biomass production in Brazil, this paper is the final part of a research that aims to study carbon capture and storage in systems of combined liquid fuels production and electricity, using biomass that is already widely available. The first study was an assessment of the performance and feasibility of BECCS in the Brazilian sugar-energy sector, with CCS of the carbon emitted in conventional combined heat and power (CHP) systems, together with the capture of CO_2 emitted in the fermentation of ethanol production (RESTREPO-VALENCIA; WALTER, 2019). In the second study, the BECCS technology was evaluated in a sugarcane plant considering electricity generation based on the not yet commercial BIG-CC technology. In this case, pre and post-combustion capture routes were considered, both based on MEA absorption (Chapter 2).

Since the previous results indicated the feasibility of carbon capture, this chapter presents the assessment of the BECCS technology in a thermoelectric plant that would use residual sugarcane biomass. It contains three main assessments: i) comparison with results from previous studies, ii) analysis of the impact of the cost of biomass, and iii) analysis of scale effects.

3.2. Materials and methods

The results of the previous cases indicate the technical and economic feasibility of carbon capture in sugarcane mills, although it was not possible to achieve an optimized arrangement, mainly due to the high demand for steam both in the industrial process and for solvent regeneration used in the capture process. This restriction had a negative impact on carbon 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 make it possible to compare the results, two power generation technologies (based on steam cycles and BIG-CC) were considered.

3.2.1. Plant localization

To assess the possible location of the thermoelectric plant, the first condition is 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 (WALTER *et al.*, 2021) and combined with data of suitable sinks for CO_2 injection. According to the Brazilian Carbon Capture Atlas, one of the most promising sites for geological storage is the sandstones of the Rio Bonito Formation, located in the Paraná Basin (KETZER *et al.*, 2016) (see details in section 2.1). Sugarcane mills located in the Paraná Basin resulted in 247 plants, as shown in Figure 3.1. It was also assumed that the thermoelectric plant should be located close to the existing electricity grid, in order to reduce connection costs.

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 pre-selected, 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 previous studies. Data on the spatial distribution of sugarcane crops in 2019 (MAPBIOMAS, 2020) 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[2] in the municipality of Planalto was selected, with 4.82 Mt crushed in 2020 (Figure 3.1). The unit is located at 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 to the nearest substation facility. More specifically, in 2019 sugarcane plantations occupied approximately 160,000 ha within a radius of 30 km centered on the mill.

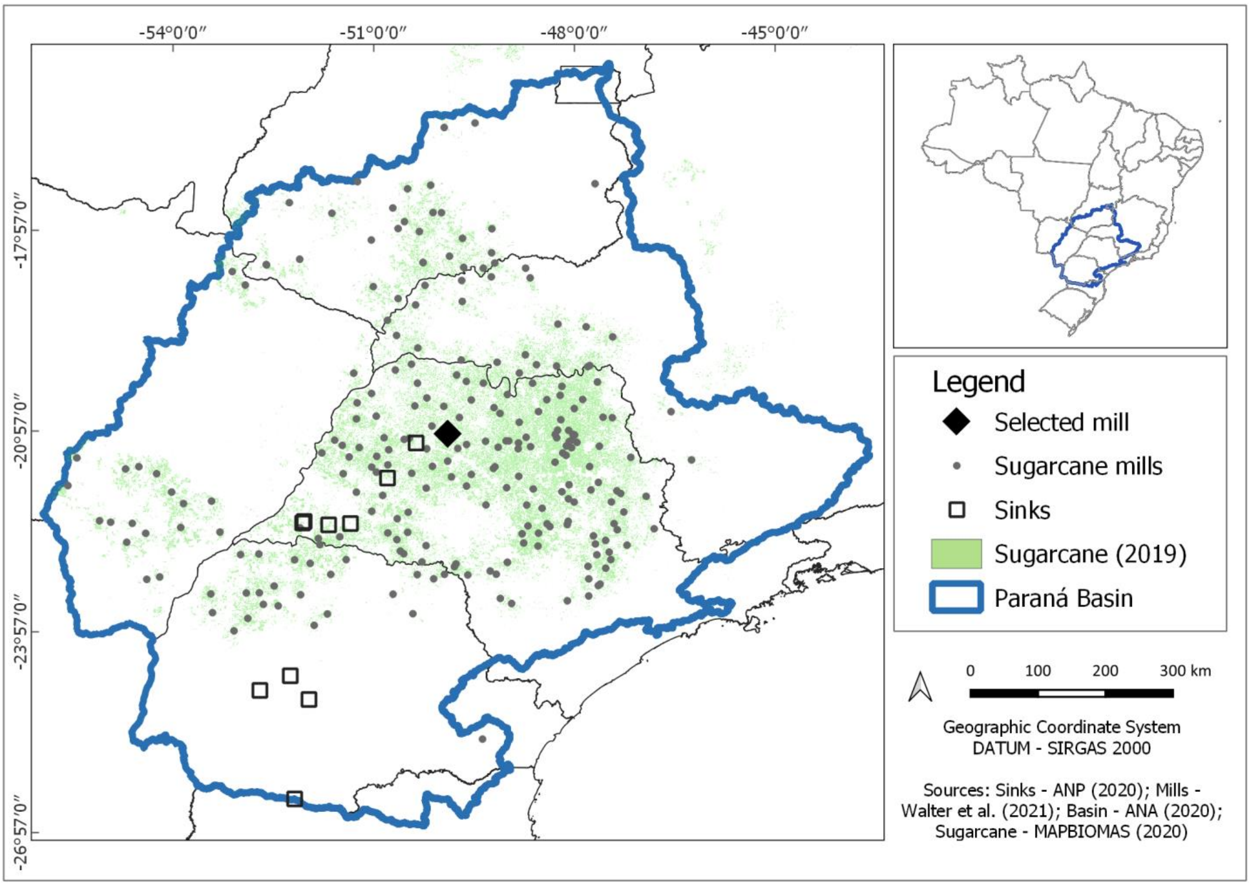

Figure 3.1 Sinks for CO_2 injection and location of existing sugarcane mills in the Paraná Basin, besides the location of the mill selected for the case study.

3.2.2. Biomass

It was assumed that the thermoelectric 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 only surplus biomass, and the contribution of additional biomass was considered in the analysis of scale effects. The sugarcane mill was considered self-sufficient in energy and it was assumed that, in order to maximize the surplus of biomass,

[2] The assumed industrial parameters are hypothetical and do not correspond exactly to the actual parameters of the mill.

electricity generation would only be to meet the internal consumption. The internal consumption of electricity per tonne of sugarcane was set at 30 kWh (MOREIRA, J. R. *et al.*, 2016). To calculate surplus biomass, it was assumed that the mill operates with a conventional steam generation system, i.e., with back-pressure steam turbine, and only during the harvest season; Table 3.1 presents the main parameters assumed. Aiming to maximize the biomass surplus, the conventional system operates with most common parameters for live steam at existing cogeneration mills (i.e., 65 bar, 480°C) and steam demand would be reduced. Bagasse availability is determined by the fiber content of the sugarcane plant, in this case 14%, which results 280 kg of bagasse per tonne of cane with 50% moisture content (PEDROSO *et al.*, 2017). The assumed lower heating value (LHV) for bagasse is 7.52 MJ/kg.

Table 3.1 Characteristics of the mill

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)	4.82
Bagasse availability per tonne of sugarcane (kg)	280 (50% moisture content)
Energy demand	
Steam process requirement per tonne of sugarcane (kg)	340
Electricity consumption per tonne of sugarcane (kWh)	30
Steam generation system	
Boiler efficiency (base LHV)	85%
Live steam parameters	65 bar/480°C

3.2.2.1. 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. Planted area of sugarcane was calculated based on the spatial distribution of sugarcane crops in 2019 according to MAPBIOMAS (2020) and one-sixth of the area was assumed to be destined for the renovation of sugarcane plantation. For each pixel occupied by sugarcane, the database from SAFmaps platform was adopted to predict the sugarcane yield, originally estimated based on regular investments in sugarcane production[3] (WALTER *et al.*, 2021). It was assumed 140 kg (on dry basis) of straw availability in the field per tonne of sugarcane (PEDROSO *et al.*, 2017).

[3] The assumed values are slightly higher in comparison to current average values, due to the lack of investments in recent years in the sugarcane sector.

On average, an amount of 4 tonnes of straw per hectare (dry basis) should be left on the ground for this study region, taking into account climatic conditions, soil conservation requirements and expected benefits for sugarcane yield (DE SOUZA, N. R. D. *et al.*, 2021; HERNANDES *et al.*, 2019).

Two possible straw recovery routes were considered and costs were estimated according to the distance from the cane field to the mill, or the thermoelectric plant. For simplicity, and to maximize the availability of biomass at the thermoelectric 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. For longer distances, the baling system was assumed, and the straw would be transported directly to the thermoelectric 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 3.2 shows the estimated amount of straw available around the mill, as function of the distances.

Table 3.2 Amount of straw available for power generation

Harvest radius; center at the thermoelectric plant	Amount of straw available[a]	Integral		Baling system	
(km)	(t)	(t)	(%)	(t)	(%)
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 (PEDROSO *et al.*, 2017).

3.2.3. Power generation technology

The thermoelectric plant operation was evaluated for an annual capacity factor of 90%. Two power technologies were considered: steam cycle based on 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.

3.2.3.1. Combustion and condensing-extraction steam turbine (CEST)

In Brazilian sugarcane mills, a more advanced variant of CEST technology has been used to generate electricity, using bagasse and straw, in relatively small amounts, as fuel. 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 burning problems can be resolved until the BECCS system enters the pilot and demonstration phases. This hypothesis is supported by the efforts made in recent years to study the phenomena, to guarantee the continuous operation of steam generators, like the SUCRE project (HERNANDES; LEAL, 2020).

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). Steam turbine has three bodies, as data presented in Table 3.3, and 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 CCS unit.

The carbon content in the dry fuel was assumed to be 46.3% for bagasse and 45% for straw, according to (RODRIGUES; WALTER; FAAIJ, 2007).The CO_2 emission from combustion was estimated with the assumption of full combustion of biomass and the flow of gases corresponds to the hypothesis of 30% excess air (LI *et al.*, 2015).

Table 3.3 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

3.2.3.2. Biomass-integrated gasification to combined cycle (BIG-CC)

Basic information about the biomass gasification process was taken from (JIN; LARSON; CELIK, 2009); details of the adaptation that was made are presented in section 2.2.1. 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. The resulting biomass derived gas (BDG) was considered a low calorific value (LCV) gas and its assumed composition is shown in Table 3.4. After leaving the gasifier, the BDG undergoes cooling and cleaning steps before feeding into the combustion chamber of the gas turbine.

Table 3.4 BDG composition – gas turbine fuel (% mol)

Component	BDG
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

To simulate the gas turbine, the characteristics of the GT11N2, a gas turbine that produces 117 MW under ISO conditions, were considered. Gas turbine operation with LCV fuel corresponds to off-design conditions. In this sense, based on RODRIGUES; FAAIJ; WALTER, (2003), two strategies were adopted to estimate the gas turbine operation: de-rating and blast-off air from compressor. The de-rating corresponds to the reduction of firing temperature to adjust operation, and the air blast-off corresponds to an extraction at the compressor discharge (already required to feed the ASU). Table 3.5 summarizes the resulting main gas turbine operation parameters when the BDG is burned, and compares them with its operation with natural gas at ISO basis.

Table 3.5 Gas turbine (GT11N2) main parameters operating with natural gas and BDG

Parameter	Natural gas at ISO basis (LHV: 47.75 MJ/kg)	GT operation with BDG (LHV: 7.1 MJ/kg)
Blast-off (kg/s)	-	35.42
De-rating (°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

A non-commercial software developed by the authors was used to simulate the gas turbine and the combined cycle. The calibration of the simulation procedure was performed by comparing the results with the GateCycle software version 6.1.4; for more details, see RESTREPO-VALENCIA (2018). The CO_2 flux in the exhaust gases was estimated from the gas turbine simulation, considering the fuel composition and total carbon oxidation.

The energy from the exhaust gases is recovered in the heat recovery steam generator (HRSG), raising the steam in two levels; afterwards, the gas stream is still used to dry the biomass. The first pressure level was set at 31.65 bar to supply a small amount of steam required by the gasifier, and the second was set at a pressure that allows for the maximization of the flow that is expanded in the steam turbine. The steam required for the CCS process is extracted from the steam turbine.

3.2.4. Capture unit

For both power generation technologies, post-combustion capture based on chemical absorption was considered. The capture efficiency was set at 90% in relation to the processed CO_2 flow (OREGGIONI *et al.*, 2015; TAGOMORI *et al.*, 2018). The flue gases from combustion would be treated with the amine solvent Cansolv, a tertiary amine used for CO_2 removal. This capture technology is the current benchmark for post combustion, selected as the base case for CCS plants based on chemical absorption, and was used in the Boundary Dam plant (JAMES *et al.*, 2019). The solvent has been compared to conventional amines and showed superior kinetics, advanced absorption capacity, and lower regeneration energy (ABU-ZAHRA; SODIQ; FERON, 2016). 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 tonne of CO_2 (NETO; SZKLO; ROCHEDO, 2021), corresponding to 1,163 kg of steam per tonne of CO_2 processed. This technology is similar to the one used by the authors in previous studies (see previous chapters) (2.6 GJ per tonne of CO_2), based on the absorption process with MEA (PEETERS; FAAIJ; TURKENBURG, 2007).

To maintain consistency with the author's previous studies, and to enable comparison of results, the CO_2 flow from ethanol fermentation at the nearby sugarcane plant was included in the assessment. It was assumed that the combustion flow is mixed with the CO_2 stream from fermentation and further sent to final CCS stages: compression, transport and storage. The CO_2 from fermentation could be considered a pure stream, therefore, no separation penalty was assigned. The main considerations for estimating the amount of CO_2 from fermentation are presented in Table 3.6. It was assumed a sugar mill with an annexed distillery (i.e., 50% of the sugarcane would be used to produce ethanol).

Energy penalties for the treatment of exhaust gases include pumping and blowing in all processes and auxiliaries; were estimated at 25.84 kW per kg/s of exhaust gases, (KHORSHIDI *et al.*, 2016).

Table 3.6 Parameters considered for estimating the CO_2 flow from fermentation

Parameter	Value	Source
Ethanol production per tonne of sugarcane (L)	86.3	(MACEDO; SEABRA; SILVA, 2008)
Ethanol density (kg/L)	0.809	(MOREIRA, J. R. *et al.*, 2016)
CO_2 production per kg of ethanol (kg)	0.96	(MOREIRA, J. R. *et al.*, 2016)
Emission index per liter of ethanol (kg)	0.78	

3.2.5. CO_2 compression

The power required for CO_2 compression was estimated based on the model proposed by MCCOLLUM; OGDEN (2006), and could be considered in two main steps. First, CO_2 is compressed from one bar to its critical pressure (73.9 bar); conservatively, it was assumed an ideal gas compression divided into five stages with intermediate cooling, and isentropic efficiency of 85% per stage. Second, already in the liquid phase, a pump (with assumed isentropic efficiency of 85%) would be used to raise the CO_2 final pressure to 150 bar.

3.2.6. 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.

3.2.7. Economic performance assessment

The economic assessment was performed based on information available in the literature. Estimates include the investment and operation and maintenance (O&M) costs for the power unit of both technologies, for the post-combustion capture with Cansolv and the CO_2 compression; transport and storage costs at a nearby potential sinkhole were estimated from DOE/NETL (2019) guidelines. All costs are presented in euro ($€_{2020}$). The discount rate assumed here was 8% and the useful life of all facilities was 25 years, considering straight-line depreciation. All capital costs refer to turn-key prices, and a location factor of 1.14 was assumed for all imported devices (TOWLER; SINNOTT, 2013); it was assumed that all the necessary equipment for the CEST technology are built in Brazil.

In practice, it was assumed that the minimum selling price (MSP) of electricity from the thermoelectric plant should be the same as the CHP unit of the neighboring plant, without CCS, on the condition that it would sell 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).

3.2.7.1. Capital costs

Due to the information available in the literature for single capacities, the capital costs were estimated according to scaling presented by Equation (3.1); C represents the cost of capital to be estimated, Q the capacity of the case under evaluation, α is the scale factor and the zero subscript indicates the reference case. Unless specific indications, below, the scale factor used was 0.6.

$$C=C_0\cdot\left(\frac{Q}{Q_0}\right)^{\alpha} \tag{3.1}$$

For the power generation technology based on CEST, capital costs were estimated in Brazilian currency (R$) from an updated function presented in GOUVELLO (2010). Equation (3.2) presents the function, already in Euro (2020), which estimates turn-key investments in Brazil, including the storage of biomass and the connection to the grid (up to 40 km away from the connection point). In the equation, C represents the capital costs, in €/kW installed, while capacity is the total installed capacity, in MW.

$$C_{CEST} = 2726\cdot\,(capacity)^{-0.334} \tag{3.2}$$

The capital cost for the power plant based on biomass gasification was estimated from JIN; LARSON; CELIK, (2009). The reference costs were assumed to be those of the n^{th} unit, and the scale factor had values ranging from 0.5 to 0.7 according to the plant area. The estimated value include 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 section 2.2.6.

The gas turbine cost was estimated for a machine equivalent to the GT11N2 (i.e., same capacity – 117 MW – and same net thermal efficiency – 34%). The procedure took into account quotations for different years (PEQUOT PUBLISHING INC, 2003, 2009, 2012, 2013, 2017), being the estimate for 2020 the result of an adjusted function, in US dollars. Finally, the value was converted to the currency of this study.

The capital costs for the capture and compression devices were estimated from VAN DER SPEK; RAMÍREZ; FAAIJ (2017). The assumed scaling factor in this case was 0.6.

3.2.7.2. Fuel costs

Different hypotheses were used to assign costs to sugarcane bagasse and straw. Initially, no cost was defined for bagasse and for straw its cost corresponded only to harvest and transport, as shown in Table 3.7. Further on, cost was assigned to biomass per unit of energy, as presented in section 3.2.9.

Table 3.7 Biomass costs in the base case

Biomass	Source	Harvest radius (km)	Harvest	Harvesting and transport costs (€/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.* (2019)

3.2.7.3. 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 in previous studies (see section 2.2.6.2). Table 3.8 summarizes the assumed percentages.

Table 3.8 Assumptions for annual operation and maintenance costs

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 (DOE/NETL, 2019)

In the case of CO_2 transport and storage stages, the DOE/NETL guidelines for costs estimates (2019) were followed. The transport cost per tonne of CO_2 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 7 to 18 € per tonne of CO_2 due to the lack of information on geological storage sites in Brazil, especially for onshore options.

3.2.8. 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 Chapters 1 and 2, and those results were used in comparison with the results presented here. To make possible the comparison, 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 as an annexed distillery. All economic parameters were updated when the results were originally presented in values different from 2020. The exchange rate 6.15 R$/€, for 2020, was used to convert values in Brazilian currency (R$) to Euro.

3.2.9. Fuel cost sensitivity

Due to commercial electricity generation, it has to 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 considered. The sensitivity analysis was performed for biomass costs in the range 0.0 to 4.0 € per GJ, as suggested by ROSSI *et al.* (2020), plus the cost of harvesting and transport in the case of straw. According to TANZER; BLOK; RAMÍREZ (2021), biomass market prices range from 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 0.79 € to 1.37 € per GJ (JORNALCANA, 2019; TAPIA CARPIO; SIMONE DE SOUZA, 2017).

3.3. Results and Discussion

This section presents results for the assessment of BECCS that would be a thermoelectric plant operating with residual sugarcane biomass. Results are divided into three main sections presenting technical and economic performance for different configurations. First, the comparison with carbon capture in a sugarcane mill is presented. Second, a fuel cost sensitivity analysis was performed. Finally, the impact of scale effects was analyzed.

3.3.1. Comparison with capturing in a sugarcane mill

Besides a sugarcane mill with capacity equal to 4.82 Mt crushed, in 2020, a thermoelectric plant would be installed. The sugarcane mill would have a cogeneration unit only to ensure self-sufficiency and the surplus biomass would be transferred to the thermoelectric plant. The results show that the mill can operate with 58% of the available bagasse, not needing straw to reach self-sufficiency. Thus, the surplus bagasse (42%) is transferred to the thermoelectric plant. Table 3.9 presents the results of surplus biomass.

Table 3.9 Annual surplus biomass from sugarcane mill

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

The thermoelectric plant could be based either on CEST or BIG-CC technology. Comparison with previous results requires that the annual CO_2 capture be equal, and then the amount of biomass required by the thermoelectric plant was calculated. In both cases, the CO_2 stream from the fermentation of the neighboring mill was added. Table 3.10 presents the results of the simulation for both thermal power plant technologies operating with CO_2 capture.

Table 3.10 Technical performance of the thermal power plants

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
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.

In order to establish the basis for comparison, previous studies (see Chapters 1 and 2) have been updated. For both energy technologies, the plant was assumed to be an attached distillery in which sugarcane is used equally for both ethanol and sugar production (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 thermoelectric 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 crushed cane per year). The global capture efficiency would be also 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 3.11 presents cost estimates and economic results for the BIG-CC and the CEST technology. 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 3,860 € per installed kW, or 11% more expensive than in the CEST case (3,492 € 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 O&M, capture expenses represent 67% of total operation costs in the BIG-CC and 61% in the CEST cases.

Here, the feasibility of capturing CO_2 in a thermoelectric plant using residual sugarcane biomass is analyzed in comparison with the results previously presented (see chapters 1 and 2), which were corrected (i.e., updated and adjusted). The results for the thermoelectric case, and the comparison, are presented in Table 3.12.

For the BIG-CC technology (CHP and power plant), the MSP of surplus electricity was estimated at 42 €/MWh, which is in line with the prices paid for bioelectricity in recent auctions, in Brazil (CCEE, 2020). For the CEST technology, the estimated MSP of electricity is 22 €/MWh in the thermoelectric case and 29 €/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 thermoelectric power plant.

Table 3.11 Cost and economic results for thermoelectric plant

Parameter		
Power plant technology	BIG-CC	CEST
Capital cost		
Gasifier island (M€)	132	-
Power unit (M€)	79	58
CO_2 capture unit (M€)	275	246
CO_2 compression unit (M€)	42	38
Fuel costs (M€/y)	7.8	6.4
O&M costs		
Gasification (M€/y)	5.3	-
Power plant (M€/y)	1.6	1.2
Capture unit (M€/y)	16.0	14.4
Compression unit (M€/y)	1.9	1.7
Transport (M€/y)	3.1	3.0
Storage (M€/y)	9 – 23	8 – 19
Performance indicators		
Electricity price (MSP) (€/MWh)	42	22
CO_2 abatement cost (€/tCO_2)	62 – 73	61 – 76

Table 3.12 Main results for CO_2 capturing in sugarcane mill or in a thermal power plant

Parameters	This study		Chapter 2	Chapter 1 (RESTREPO-VALENCIA; WALTER, 2019)
	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) (€/MWh)	42	22	42	29
CO_2 abatement cost (€/tCO_2)	62 – 73	61 – 72	60 – 71	68 – 79

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

3.3.2. Impact of fuel costs

The general case is that the owners of the sugarcane mill and the thermoelectric plant are different agents, which raises the question of the impact of biomass costs on the economic results of capturing and storing carbon. This was done by repeating the procedure that led to the results presented in Table 3.12 (where only the costs of harvesting and transporting the straw were considered, i.e., which are equivalent to 0.75 €/GJ for the BIG-CC case, and 0.67 €/GJ for the CEST case), now varying the energy cost in the range 0 to 5 € per GJ. In practice, 0 to 5 €/GJ is the cost considered for bagasse, and the values in the range were added to the costs of collecting and transporting straw (see Table 3.7).

Figure 3.2 shows the variation in estimate CO_2 costs for different average biomass costs (bagasse and straw). Here, it was arbitrarily assumed that costs over 90 € per tonne of CO_2 stored would lead to a non-competitiveness 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 (IEAGHG, 2018). In this sense, it is possible to conclude that the maximum (average) cost of sugarcane biomass for a BECCS thermoelectric unit to be feasible is 3 €/GJ (in the case of minimum costs of storing CO_2). This value also serves as a reference for the feasibility analysis in the case of using other biomasses.

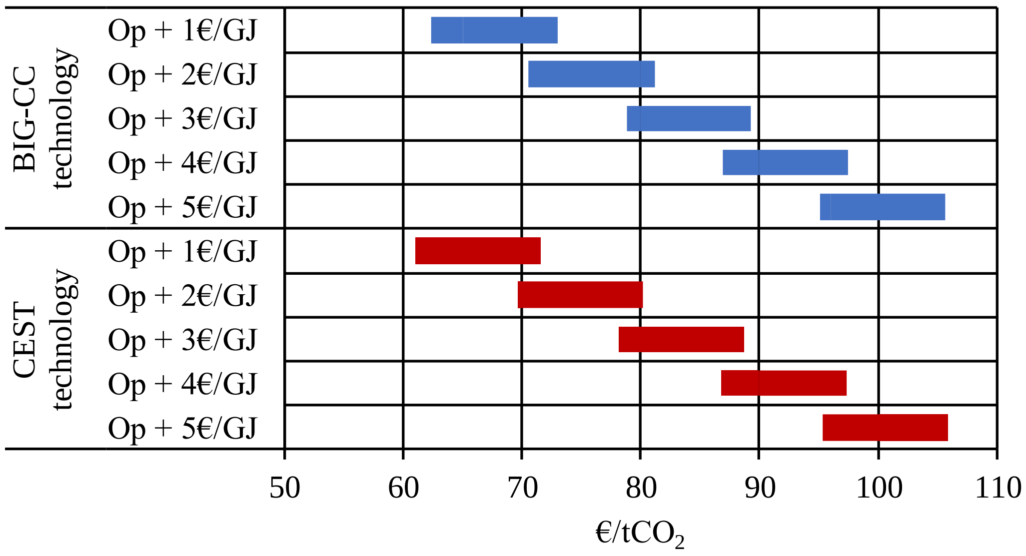

Figure 3.2 CO_2 abatement costs as function of biomass costs, for BIG-CC and CEST technologies; Op refers to the costs of collecting and transporting straw.

3.3.3. Scaling effects

A second important aspect in the analysis is the consideration of the scale effects of BECCS systems, assuming greater capacity for generating electricity and, consequently, greater capture of carbon dioxide. The electric generation capacity was expanded by taking on the collection of straw available in the field within a circle with a maximum radius of 50 km, with the thermoelectric plant as the center (see Table 3.2). 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 1 € per GJ, and this value was added to the operating and transporting costs for straw, as reported in Table 3.7. 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 thermoelectric plant and in the capture unit.

3.3.3.1. <u>CEST technology</u>

Table 3.13 presents results for different capture capacities for electricity generation based on 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 54 – 65 € per tonne of CO_2, which is almost 20% lower compared to the reference case.

Table 3.13 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	1,522	2,128
Electricity price (MSP) (€/MWh)	22	22	22	22
CO_2 abatement cost (€/tCO_2)	69 – 79	63 – 74	59 – 69	54 – 65

3.3.3.2. BIG-CC technology

Table 3.14 presents the results of scaling effects when electric generation is based on BIG-CC technology. As a single gas turbine model was considered, the analysis was performed by increasing the number of gas turbines, and the same for the number of gasifier inlands. 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 abatement CO_2 costs with the scale is observed. 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 would not exceed a 20 km radius (1.28 $MtCO_2$), and the thermoelectric plant would have only one BIG-CC module. To make a thermoelectric plant with four BIG-CC modules viable, it would be necessary to collect straw beyond the 50 km radius that was considered the limit in this study. The CO_2 abatement cost could be reduced to 57 – 68 € per tonne of CO_2, which is slightly higher than best figure for CEST technology.

Table 3.14 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	1,669	2,511
Electricity price (MSP) (€/MWh)	42	42	42
CO_2 abatement cost (€/tCO_2)	71 – 81	62 – 73	57 – 68

3.3.4. Thermoelectricity feasibility

Comparisons were made of the capture results in thermoelectric plants using residual sugarcane biomass with those of the cogeneration facilities, previously presented. The results of the economic evaluation show that the costs are not higher, and may even be lower, than in the capture in cogeneration systems.. Finally, a case of a stand-alone thermoelectricity plant, without including the CO_2 from fermentation, was assessed. Table 3.15 and Table 3.16 presents results for CEST and BIG-CC technology, 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.

The preliminary report from IPCC for the sixth assessment report WGIII (IPCC, 2021), presents costs for BECCS technology collected from multiple academic references, values that are between 13 – 355[4] €/tCO_2. For the minimum values in the range, rigorously only the capture of CO_2 from fermentation in ethanol production would be competitive. These estimated reported costs, under Brazilian conditions, are 24 €/tCO_2 (MOREIRA, J. R. *et al.*, 2016) and 23 €/tCO_2 (RESTREPO-VALENCIA; WALTER, 2019). The alternative of capturing CO_2 from fermentation at a sugar plant could be in small-scale case, negatively impacting costs, and CO_2 transportation represents a considerable cost factor. TAGOMORI *et al*. (2018) showed that CO_2

[4] Values in US dollars ($) were converted to euro using the average exchange rate in 2020 (1.12 $/€).

capture from ethanol production needs to be combined with cogeneration plants to enable the implementation of CO_2 transport infrastructure in Brazil. Even so, this type of BECCS arrangement may not be sufficient and scale gains may require CO_2 flows from fossil sources to ensure larger and regular flows (FORMANN *et al.*, 2020). As the range suggested by the IPCC is wide, all the results reported in this thesis have estimated values in the lower part of the range, but as BECCS is not a mature technology (TRL 5-6), the feasibility of the first units in Brazil is under many uncertainties.

Table 3.15 Results for different CO_2 capture capacities for the CEST technology without capturing from 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	1,009	1,537	2,143
Electricity price (MSP) (€/MWh)	22	22	22	22
CO_2 abatement cost (€/tCO_2)	77 – 87	68 – 79	62 – 72	56 – 67

Table 3.16 Results for different CO_2 capture capacities for the BIG-CC technology without capturing from 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	1,684	2,526
Electricity price (MSP) (€/MWh)	42	42	42
CO_2 abatement cost (€/tCO_2)	78 – 89	65 – 76	59 – 70

An important aspect is that CCS is one of the alternatives in the portfolio of actions so that climate goals can be achieved and, for similar costs, capturing carbon in a thermoelectric plant that operates with residual sugarcane biomass is a desirable option in relation to capture in a fossil fuel plant.

3.4. Conclusions

In this chapter, the feasibility of CO_2 capture in thermoelectric 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 €/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 decreases, as does its economic impact. 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 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 note that it was here assumed 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 the generators. However, 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 addressed.

4. CONCLUSIONS

4.1. Overall conclusions

This section presents general conclusions and final considerations of the evaluation of BECCS systems in sugarcane mills and thermoelectric plants that use residual sugarcane biomass, considering only the Brazilian energy context. In this thesis, three configurations of BECCS systems were evaluated, focusing on maximizing carbon capture in the combined production of ethanol and electricity.

For power production, both the conventional CEST and the BIG-CC technologies were considered. Current practices in the sugar-energy sector include the operation of cogeneration units, most of which still have back-pressure steam turbines. Although there have been advances, not so many plants have CHP CEST systems, they operate with reduced use of straw (due to operational problems), and medium parameters for live steam being are more common (i.e., 65 bar, 480°C). Here, BECCS systems were modeled assuming the live steam parameters that result in higher efficiency (i.e., 120 bar, 535°C), considering that this would be the practice adopted by the industry in the coming years when the BECCS systems could be in the pilot and demonstration phases.

The consideration of BIG-CC systems is due to the objective of identifying possible advantages of this technology, still relatively far from being commercial, in relation to conventional steam systems. However, for both CHP and thermoelectric systems, and from the point of view of CO_2 capture, clear advantages of the BIG-CC technology were not identified. Despite the greater efficiency of electricity generation, the combination of an immature technology with CO_2 capture increases the risks. Thus, BIG-CC systems can only be considered in a medium to long term horizon, and only if all restrictions associated with large-scale biomass gasification and fuel gas cleaning are overcome. So, for the BECCS pilot and demonstration units, CEST technology is the one to consider.

Capturing CO_2 from ethanol fermentation in sugarcane plants is the best opportunity in the sector. As might be expected, since CO_2 is already available practically pure, the energy penalties are less than the CO_2 capture from combustion. Based on estimates of mitigation CO_2 costs in the coming years – 35 €/tCO_2 (IEAGHG, 2018)–, this route is the only one that is clearly competitive. In the Brazilian context, this is the alternative that should be prioritized and could be dealt with without linking to the capture of CO_2 from combustion, but for that it is important to define the adequate logistics to combine the flow of several mills, and have benefits of scale (ROCHEDO, PEDRO R.R. COSTA *et al.*, 2016). Although CO_2 from fermentation does not represent the largest share, consideration of the combined capture of CO_2 from fermentation and combustion helps to improve the viability of the alternatives evaluated here. As shown in Chapter 3, this impact is minimized in the case of larger thermoelectric plants.

By comparison, capturing CO_2 from biomass combustion has significant energy penalties. Combined with the demand of process steam, the heat demand for amine recovery makes it difficult to integrate the capture system to a mill, which ends up restricting the amount of CO_2 captured when considering cogeneration systems. This is the main reason for the consideration in one of the cases of thermal power plants, instead of cogeneration systems.

Comparing on a similar basis, the assessed results show the advantage of capturing CO_2 in a thermal power plant installed next to a mill, advantage that increase with the capacity of the thermal power plant. Thus, one conclusion is that it is worth collecting biomass (straw) from neighboring sugarcane fields. However, the costs of CO_2 capturing depend on the cost of biomass and the conclusion is valid for biomass with a cost of less than 2 – 3 €/GJ.

In the case of BIG-CC systems operating in cogeneration mode, the feasibility of the pre-combustion capture alternative was analyzed. This route has a smaller impact on the sale of surplus electricity, but the capture is lower compared to the results of the post-combustion route (0.82 versus 1.44 $MtCO_2$/year). In the cases presented in Chapter 2, the smaller scale has a negative impact on costs. Estimated capture costs range from 52 – 63 €/tCO_2 for post-combustion and 60 – 71 €/tCO_2 for pre-combustion. Due to these results, only post-combustion capture systems were considered when analyzing the thermoelectric plants.

The comparison with the capture of CO_2 in natural gas power plants must consider the particularities of the cases presented here. First, that energy penalties in biomass power units are proportionately higher, mainly due to the low efficiency of electrical generation. Second, the scale of capture and its impact on costs is an aspect to be taken into account. Third, and very importantly, a BECCS system that operates with sustainable biomass contributes with negative emissions, and not just with reduced emissions.

For CO_2 capture in cogeneration units, the results showed that investments in CCS are much higher than for generating surplus electricity. In this sense, it would be necessary for investors to have a different priority, that is, focus on reducing emissions and selling carbon credits instead of generating electricity. In any case, the opportunity cost of selling electricity impacts the feasibility of capturing carbon. The estimated minimum selling prices (MSP) of electricity are, in general, in line with the contracted values of the winning biomass projects in the auctions held in Brazil. For the BIG-CC technology, despite the assumption of the cost of the n^{th} plant, the electricity MSP are slightly higher than those for the CEST technology.

Estimated CO_2 abatement costs in thermoelectric power plants and cogeneration systems are high when compared to the current price of carbon (e.g. under the CO_2 European Emission Allowances the carbon price in 2020 was 26 €/tCO_2 (CO2 EUROPEAN EMISSION ALLOWANCES, 2019)). Assuming post-combustion capture for the BIG-CC cases, CO_2 abatement costs ranged from 62–73 €/tCO_2 in power plants, and 60–71 €/tCO_2 for cogeneration. In the CEST technology case, costs ranged from 61–72 €/tCO_2 for power plants, and 68–79 €/tCO_2 for CHP. Even in the case of larger thermal power plants (54–65 €/tCO_2 – CEST; 57–68 €/tCO_2 – BIG-CC), abatement costs are higher than those recently observed in the carbon market. However, in the coming decades, negative emissions will be needed in electricity generation to compensate for the remaining fossil-based thermal systems and, in this sense, it will be essential to have bioenergy systems based on sustainable and low-cost biomass, in places where CO_2 capture is possible. Thus, it is concluded that it will be crucial to enable the capture under the conditions studied here.

4.2. Recommendations

Bioenergy in Brazil represents a fundamental alternative for the energy transition to renewable and sustainable systems. In Brazil, there are clear opportunities in association with the production of biofuels and bioelectricity, in particular from sugarcane, because of the great availability of residual biomass.

Regarding the capture process, because of the significant energy penalties, other technologies should be studied (i.e., membranes, adsorption). As for geological storage, there is still no adequate knowledge about suitable locations and costs, and these are points where research is needed. In addition, given the concentration of mills in the center-south of Brazil, the creation of hubs for capturing and transporting CO_2 is also a relevant subject for research.

Future studies are also recommended considering alternatives for the use of CO_2 to be captured, for example, in the production of chemicals or synthetic fuels, in or near the plants.

All regulatory aspects related to the process of capturing and storing CO_2, in the Brazilian context, should be the focus of future specific studies. Currently, there is no definition of responsibilities, which makes it impossible to sell credits due to capture. Nor is there a definition of procedures regarding the storage itself, monitoring of the reservoirs and the necessary action plans in case of leakage.

Finally, for the evaluation of storage alternatives, which in this thesis was only considered the Paraná Basin, it is important that other locations would be considered.

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APPENDIX

A. SUGARCANE STRAW AND ITS USE AS FUEL

The production of sugarcane in Brazil in the 2020/2021 harvest attained 658 million metric tonnes, with a 2.3% growth in comparison with previous period (OBSERVATÓRIO DA CANA, 2022). For 2019, sugarcane sector represented almost 3% of Brazil's gross domestic product (GDP), accounting more than 15% of the national agricultural production value (IBGE, 2022). The sugarcane represents a well-established sector, and has frequently sought to improve processes.

In the last decades, the interest in mechanical harvesting and in improving cogeneration systems have been priority. The latter, has gained considerable importance due to the opportunities of exporting surplus electricity to the grid. For the power units, the biomass available at sugarcane mill – bagasse, and recently, straw – has been used as fuel in boilers. The sugarcane straw refers to a fibrous and heterogeneous residue, made up of the tops and the green leaves tangled to sugarcane stalks after harvesting (FRANCO *et al.*, 2013; WATANABE *et al.*, 2020). With the expanding global demand for bioenergy, the straw has been seen as a promising feedstock for second-generation ethanol and bioelectricity generation (HERNANDES *et al.*, 2019). Nevertheless, not all the straw could be used for bioenergy purposes, as the straw mulching on soil results in agronomic benefits as nutrient recycling, soil erosion control, soil biodiversity protection, keeping soil carbon stocks, soil temperature and weed control (CARVALHO *et al.*, 2017; HERNANDES; LEAL, 2020).

The SUCRE Project (2015 – 2020) aimed to establish a coherent plan to remove straw from the field without risking soil health, controlling GHG emissions, and enhancing sugarcane yield. According to the findings, excessive straw removal impair soil quality and increase soil and nutrient losses by soil erosion. On the contrary, the straw removal in low rates cause minimum impacts on soil quality. The results recommend to perform a balance between bioenergy production and soil quality, depending on agronomic conditions which are affected by multiple factors as location, weather, harvesting seasons, slope (HERNANDES; LEAL, 2020). For example, in HERNANDES *et al.* (2019), in which the study area is located in the Brazilian center-south region, considering a minimum amount of straw left on the ground, approximately 63% of the straw is available to be collected and used for bioenergy purposes.

Straw recovery routes

Straws quality and availability depends on how the biomass is recovered for being sent to boilers. Three routes for recovering straw from the field are used nowadays in the Brazilian sugarcane sector: integral harvesting, in which straw goes together with the stalks processed to the mill, where it can be separated at a Dry Cleaning Systems (DCS); baling; and by the hay harvester straw collection route. The baling and integral harvesting routes are briefly discussed here.

For baling system (HERNANDES; LEAL, 2020; SAMPAIO *et al.*, 2019; SOARES *et al.*, 2019), the straw is typically left in the field for 4 to 15 days for drying (until 10% moisture content), after sugarcane harvesting and before windrowing. If straw goes to baling process with high moisture content, the material could exceed the capacity of the baling machine. After windrowing, the baler collects straw from the field, compresses it, and ties it into prismatic bales with about half tonne each. The baled material is transported to the beneficiation plant; first transported to the edge of the field, arranged in piles and then loaded onto a semi-trailer to their final destination. At the factory, baled straw requires unpacking, sieving and shredding.

Alternatively, integral harvesting (CARDOSO, 2014; HERNANDES; LEAL, 2020; SOARES *et al.*, 2019) does not need windrowing as it does not recover straw from the field. The straw is not separated from cane billets during harvesting, so both, straw and sugarcane, are directly transported to the mill. At the mill, straw requires to be separated from the cane billet, which occurs in the dry-cleaning system. After separation, it also requires screening and shredding. The benefits of integral harvesting could include reducing subsequent straw harvesting operations and a decrease in mineral impurities due to non-contact with the soil. Furthermore, it is not necessary drying. Even so, fleet equipment such as transloaders is needed, which results in higher costs of biomass per mass transported. As for the amount of straw available at the mill, the full harvest sends a higher percentage of straw with the cane, as approximately 6% of a typical load is straw due to inefficient cleaning of the harvester.

In fact, straw recovery is a process that incorporates mineral impurities into the biomass not only by windrowing, as the harvesting process itself also contributes to the increase in impurities. It is estimated that mechanical harvesting increases mineral impurities by up to four times compared to conventional harvesting. And the windrowing operation in the field should increase almost three times.

The SUCRE project (HERNANDES; LEAL, 2020) concludes that collecting straw is a process that incorporates mineral impurities into the biomass. Moreover, the use of the straw as raw material, with the combined use of bagasse for burning in boilers, may cause serious operational and maintenance problems in the industry. The field tests demonstrate that reducing the speed of harvester extractors allows for an increase in the amount of biomass transported with the billets and may reduce fuel consumption and increase the operational capacity of the process. Total recovery costs and emissions depend on the mill and field parameters, especially the amount of straw recovered per hectare and the average transport distance. The cost of whole harvesting is benefited by a small amount of straw due to the lower load density loss, while the cost per bale is higher for small amounts of straw per hectare due to the low operational efficiency of the equipment. For some mills, the best option may be a combination of baling and integral harvesting.

Sugarcane straw and bagasse burnt in biomass boilers

For feeding boilers of CHP systems, it is fundamental to consider biomass properties. Unprocessed straw is typically composed by 50% – 60% of dry leaves and 40% – 50% sugarcane tops (FRANCO *et al.*, 2013), and its properties differ from bagasse as Table A.1 shows. The straw presents higher ash content, and its moisture content varies more in comparison with bagasse; however, the straw has an advantage due to its heating value. The chemical composition, based on the ultimate analysis, is presented in Table A.2. From the elemental analysis of biomass, it can be seen a small variation in the concentrations of carbon and hydrogen, while straw has two times more nitrogen and sulfur and chlorine content is ten times higher.

Table A.1 Bagasse and straw properties

Biomass	Bagasse	Straw
Moisture content	48% – 52%	12% – 45%
Ash content (dry basis)	2% – 8%	6% – 20%
Particle size	99% < 15 mm	90% > 90 mm
HHV(MJ/kg)	18 – 19	16 – 18
LHV (MJ/kg)	7 – 8	6 – 15

Adapted from SOARES *et al*. (2019)

Table A.2 Ultimate analysis of sugarcane biomass

Weigh % – dry basis	Bagasse [b]	Straw [b]
Carbon	40 – 44	38 – 42
Hydrogen	6.0 – 7.0	5.5 – 7.0
Nitrogen	0.2 – 0.3	0.5 – 0.6
Sulphur	0.09 – 0.11	0.12 – 0.20-
Chlorine	0.02 – 0.05	0.2 – 0.4

Adapted from RODRIGUES; WALTER; FAAIJ (2007) and SOARES *et al*. (2019)

HHV values for bagasse and straw are similar, but there are significant differences in LHV due to moisture content. The straw coming from the bale route shows moisture close to 15%, while integral harvest results in 45% moisture, similar to bagasse (HERNANDES; LEAL, 2020).

Generally, a mixture of bagasse and straw is available, while boilers are designed to burn bagasse; thus, feeding it straw can cause operational problems. This fact, summed up with other differences between bagasse and straw, such as particle size and density, can affect the boiler's combustion performance, reduce efficiency and durability, and increase maintenance costs. Furthermore, the straw can contribute to the formation and emission of toxic compounds.

In the boiler feeder, a mixture of bagasse and straw can result in biomass compaction, instability, and risk of choking (SOARES *et al.*, 2019). Different granulometry, moisture content, and density may cause operational instability in a boiler projected to operate only with bagasse. Physical differences may lock the furnace feeder and, furthermore, the own mixture of straw and bagasse could start ignition outside the equipment (MANTELATTO; CARVALHO; REGIS, 2019).

The combustion of bagasse and straw in a boiler has to be considered as a turbulent flow at a very high temperature (MANTELATTO; CARVALHO; REGIS, 2019). In these conditions, the content of inorganic elements promotes volatile material formation. In combustion, aerosol, fouling/slagging, and corrosion on the heat exchange surfaces of the boiler are primarily caused by chlorine, sulfur, and potassium. Chlorine is one of the primary elements responsible for vaporization, as well as a component of dioxins, which are highly toxic compounds found in exhaust gases. The presence of sulfur, potassium, and chlorine in biomass, combined with high temperatures, results in the formation of hydrogen chloride, sulfur dioxide and potassium chloride, which are the elements responsible for deposit and incrustations formation in boilers. In the case of ashes, the high concentrations of potassium, sodium, zinc, plumb, sulfur, and chlorine, when vaporized and subsequently condensated at the heat exchange surfaces (i.e., tubes), lead to deposit formation and are cataloged as a potential emissary of particulate material. In the case of corrosion, the risk is located also on heat exchange surfaces when the inorganic components release hydrogen chloride, which attacks the surfaces and causes the dissolution of the protective layer (i.e., active oxidation).

The study performed by the SUCRE project evaluated the chemical composition of biomass ash, and the impacts on boiler operating with pure bagasse and with a mixture of bagasse and straw in different ratios (for further details see HERNANDES; LEAL (2020)).The ash composition indicated increased concentrations of potassium, sulfur, and chlorine in mixtures in comparison with sugarcane bagasse. The chlorine content found in ashes of mixtures bagasse-straw can be five times higher than that found in ash from bagasse. Conversely, in many cases it was observed greater concentration of alkali earth metals, such as calcium and magnesium, which may lead to the reduction in the potential deposition at high temperatures (MIL *et al.*, 2021). In terms of corrosion, both operations presented risks. The use as fuel of bagasse and straw mixtures increased the concentrations of elements such as potassium, sulfur, and chlorine. In most of the cases, the fouling composition showed high concentrations of potassium and sulfur. The higher the chlorine concentration, the greater the volatilization of those elements in the boiler, resulting in the formation of silicates and chlorides.

To conclude, the use of straw as fuel in boilers, even when combined with bagasse, has caused serious operational problems. The feeding may suffer instability and risk of choke, and heat exchange surfaces (i.e., superheater, economizer and preheater) are impacted by slagging, corrosion, and fouling. For the use of straw as fuel in boilers, it is suggested to previously analyze its physical and chemical properties to assess the effect of the biomass composition on the potential formation of fouling, slagging and, consequently, corrosion.

Here, as in conventional steam power cycles (CHP or power plants), it is assumed that a large amount of straw is burned, it is assumed that the boiler operation problems would be overcome in the future, for example, with the design of new steam generators.

B. TAXES AND CHARGES

Table B.1 presents assumptions made in the economic assessment in this thesis. Parameters represent taxes and charges incident to investments in the sugarcane industry in Brazil. All values were updated to €$_{2020}$, using the average exchange rate in 2020 (6.15 R$/€ and 1.12 US$/€). The Harmonized Index of Consumer Prices (HICP) was adopted to update data to the year of reference, from values originally obtained in euro or US dollar. For values in Brazilian currency, data was updated with the market general index price (*Índice geral de preços do mercado – IGP-M*). In all the cases, the investments were supposed as a single flow in year 0.

Table B.1 Economic assumptions in all cases

Parameter	**Value**
Project lifetime	25 years
Discount rate[a]	8%
Depreciation	25 years (linear)
Location factor[b]	1.14
Contribution to Social Security Financing (*PIS* and *Confins*)	9.25% of electricity revenue
Transmission fees (*Tarifa de uso da transmissão – TUST*) [c]	2.58 € per MWh sold
Inspection fee for electricity services (T*axa de fiscalização – TFSEE*)	0.5% of electricity revenue
Income tax	25%
Social contribution on net income (Contribuição social sobre lucro líquido – CSLL)	9%

[a] The assessment presented in Chapter 1 explores different discount rate: 8%, 10% and 12%.
[b] (TOWLER; SINNOTT, 2013); only applied to the assessment presented in Chapter 3 assessment. Original value R$ 10.95 (RIBEIRO, 2018).

C. Electronic supplementary information

BECCS opportunities in Brazil: comparison of pre and post-combustion capture in a typical sugarcane mill

Sara Restrepo-Valencia & Arnaldo Walter

Technical performance

Table C.1. Gas turbine (GT11N2) main parameters operating with natural gas and simulation results operating with BDG

Parameter	Natural gas (LHV: 47.75 MJ/kg) at ISO basis.	GT operation in BIG-CC (Pre-combustion CCUS case)	GT operation in BIG-CC (Post-combustion CCUS and reference case)
Compressor pressure ratio	15.03	14.68	15.45
Fuel flow (kg/s)	6.99	28.20	48.10
Combustion temperature (°C)	1191.0	1191.0	1154.0
Gross power (MW)	116.7	112.0	117.0
Exhaust temperature (°C)	530.86	539.84	516.25
Thermal efficiency	35%	34%	34%
Compressor isentropic efficiency	0.907	0.911	0.901
Mechanical efficiency	0.96	0.96	0.96
Alternator efficiency	0.96	0.96	0.96
Auxiliary power (kW)	650	650	650
De-rating (°C)	-	-	37
Blast-off (kg/s)	-	36.33	35.42

Table C.2 Configuration parameters of CCUS integrated to a sugarcane mill

Parameter	Reference case		BIG-CC + Pre-combustion CCUS		BIG-CC + Post-combustion CCUS	
	Harvest season	Out of season	Harvest season	Out of season	Harvest season	Out of season
Mill capacity (Mt/y)	3.3		4.2		4.9	
Sugarcane processing steam demand (kg/s)	49.51	-	63.01	-	73.52	-
Capture unit steam demand (kg/s)	-	-	22.47	22.47	46.37	46.37
<u>HRSG + Steam turbine</u>						
Pinch point (°C)	5		5		5	
Steam turbine isentropic efficiency	85%		85%		85%	
Alternator efficiency	99%		99%		99%	
Steam raised pressure – 1p (bar)	31.65		31.65		31.65	
Steam raised flow – 1p (kg/s)	6.37		6.54		6.37	
Steam raised pressure – 2p (bar)	20		25		20	
Steam raised flow – 2p (kg/s)	51.14	51.14	50.34	45.76	51.14	51.14
Steam raised temperature – 2p (°C)	350	350	380	480	350	350
Desuperheater mass flow (kg/s)	0.19	-	0.30	2.95	0.19	0.19
Steam expanded low-pressure body (kg/s)	-	-	0.50	26.25	-	-
Steam pressure at the condenser	2.5	0.096	0.096	0.096	2.5	2.5
<u>Additional conventional steam generator</u>						
Boiler efficiency	-		85%		85%	
Inlet water temperature (°C)	-		90		90	
Steam turbine isentropic efficiency	-		72%		72%	
Steam raised pressure (bar)	-		20	-	20	-
Steam raised temperature (°C)	-		310	-	310	-
Steam raised flow – (kg/s)	-		35.34	-	68.55	-

Detailed cost estimation results

Table C.3 Capital cost estimate for the **reference** case

Plant area / sub-unit	Reference for cost estimation	Unit of capacity	Reference capacity Q_0	Required capacity Q	Scaling exponent *f*	Cost of reference[1] C_0	Cost per unit C	Overnight cost[2]	Overnight cost[3]
Gasifier island						(M$_{2003}$)	(M$_{2003}$)	(M$_{2003}$)	**(M€$_{2020}$)**
Feed preparation	(Jin et al., 2009)	kg/s wet biomass to gasifier	32.8	30.29	0.77	15.6	14.73	23.5	24.5
Pressurized gasifier	(Jin et al., 2009)	kg/s dry biomass to gasifier	26.3	24.23	0.70	11.4	10.75	17.1	17.9
Ash cyclone	(Jin et al., 2009)	kg/s BDG	49.90	46.04	0.70	0.204	0.19	0.31	0.3
Lock-hopper N_2 boost compressor	(Jin et al., 2009)	MW consumed	0.330	0.248	0.67	0.421	0.35	0.44	0.5
Gas clean-up						(M$_{2003}$)	(M$_{2003}$)	(M$_{2003}$)	**(M€$_{2020}$)**
Syngas cooler	(Jin et al., 2009)	kg/s BDG	49.90	46.04	0.60	22.3	21.26	33.93	35.3
Ceramic filter	(Jin et al., 2009)	kg/s BDG	49.90	46.04	0.65	8.10	7.68	12.26	12.8
ASU						(M$_{2003}$)	(M$_{2003}$)	(M$_{2003}$)	**(M€$_{2020}$)**
Integrated ASU	(Jin et al., 2009)	kg/s pure O_2	18.00	8.31	0.50	20.3	13.80	17.52	18.3
O_2 compressor	(Jin et al., 2009)	MW consumed	5.30	2.62	0.67	3.60	2.26	2.86	3.0
N_2 compressor	(Jin et al., 2009)	MW consumed	10.80	4.31	0.67	4.40	2.35	2.99	3.1
Power island						(M$_{2003}$)	(M$_{2003}$)	(M$_{2003}$)	**(M€$_{2020}$)**
Gas turbine[4]	(Pequot Publishing Inc, 2003)							33.24	34.6
HRSG and heat exchangers	(Jin et al., 2009)	MW_{th} heat duty	433	145	1.00	50.3	16.84	25.86	26.9
Steam turbine	(Jin et al., 2009)	Gross MW	190	40	0.67	57.0	20.20	25.65	26.7

[1] Original value from reference.

[2] For further details, see note *e* from Table 9 from (JIN; LARSON; CELIK, 2009).

[3] Values in US dollars ($) were converted to euro using the average exchange rate in 2003 (1.26 $/€) and then updated to 2020 with Harmonized Index of Consumer Prices (All Items for European Union).

[4] The turn-key price for the GT11N2 gas turbine, in US dollar, was used and then converted into the currency of this study.

Table C.4 Capital cost estimate for the **pre-combustion** case

Plant area / sub-unit	Reference for cost estimation	Unit of capacity	Reference capacity Q_0	Required capacity Q	Scaling exponent *F*	Cost of reference[5] C_0	Cost per unit C	Overnight cost[6]	Overnight cost[7]
Gasifier island						(M$\$_{2003}$)	(M$\$_{2003}$)	(M$\$_{2003}$)	**(M€$_{2020}$)**
Feed preparation	(Jin et al., 2009)	kg/s wet biomass to gasifier	32.8	31.07	0.77	15.6	15.02	24.0	25.0
Pressurized gasifier	(Jin et al., 2009)	kg/s dry biomass to gasifier	26.3	24.86	0.70	11.4	10.94	17.0	18.2
Ash cyclone	(Jin et al., 2009)	kg/s BDG	49.90	47.23	0.70	0.204	0.20	0.31	0.3
Lock-hopper N_2 boost compressor	(Jin et al., 2009)	MW consumed	0.330	0.277	0.67	0.421	0.37	0.48	0.5
Gas clean-up						(M$\$_{2003}$)	(M$\$_{2003}$)	(M$\$_{2003}$)	**(M€$_{2020}$)**
Syngas cooler	(Jin et al., 2009)	kg/s BDG	49.90	47.23	0.60	22.3	21.59	34.46	35.9
Ceramic filter	(Jin et al., 2009)	kg/s BDG	49.90	47.23	0.65	8.10	7.81	12.46	13.0
ASU						(M$\$_{2003}$)	(M$\$_{2003}$)	(M$\$_{2003}$)	**(M€$_{2020}$)**
Integrated ASU	(Jin et al., 2009)	kg/s pure O_2	18.00	8.53	0.50	20.3	13.98	17.75	18.5
O_2 compressor	(Jin et al., 2009)	MW consumed	5.30	2.68	0.67	3.60	2.30	2.91	3.0
N_2 compressor	(Jin et al., 2009)	MW consumed	10.80	4.24	0.67	4.40	2.33	2.96	3.1
Power island						(M$\$_{2003}$)	(M$\$_{2003}$)	(M$\$_{2003}$)	**(M€$_{2020}$)**
Gas turbine[8]	(Pequot Publishing Inc, 2003)							33.24	34.6
HRSG and heat exchangers	(Jin et al. 2009)	MW_{th} heat duty	433	146	1.00	50.3	16.95	26.02	27.1
Steam turbine	(Jin et al., 2009)	Gross MW	190	35	0.67	57.0	18.26	23.19	24.2
									(M€$_{2020}$)
Additional conventional steam generator[9]	(Restrepo-Valencia and Walter, 2019)	Gross MW		11					10.2
CCUS						(M€$_{2014}$)	(M€$_{2014}$)	(M€$_{2014}$)	**(M€$_{2020}$)**
Capture unit	(Van der Spek et al., 2017)	kg/s CO_2 captured flow	71.9	19.03	0.6	326	146.9	146.9	156.1
Compression train	(Van der Spek et al., 2017)	kg/s CO_2 compressed flow	71.9	34.12	0.6	44	28.1	28.1	29.1

[5] Original value from reference.

[6] For further details, see note *e* from Table 9 from (JIN; LARSON; CELIK, 2009).

[7] Values in US dollars ($) were converted to Euro using the average exchange rate in 2003 (1.26 $/€), and then updated to 2020 with Harmonized Index of Consumer Prices (All Items for European Union).

[8] The turn-key price for the GT11N2 gas turbine, in US dollar, was used and then converted into the currency of this study.

[9] The equation taken from reference estimates the turn-key investments in Brazilian currency (R$), as function of installed capacity. Values in R$$_{2014}$ were updated using the Brazilian general price index and then converted into euro using the exchange rate by 30/06/2020 (6.15 R$/€).

Table C.5 Capital cost estimate for the **post-combustion** case

Plant area / sub-unit	Reference for cost estimation	Unit of capacity	Reference capacity Q_0	Required capacity Q	Scaling exponent *f*	Cost of reference[10] C_0	Cost per unit C	Overnight cost[11]	Overnight cost[12]
Gasifier island						(M$2003)	(M$2003)	(M$2003)	**(M€2020)**
Feed preparation	(Jin et al., 2009)	kg/s wet biomass to gasifier	32.8	30.29	0.77	15.6	14.73	23.5	24.5
Pressurized gasifier	(Jin et al., 2009)	kg/s dry biomass to gasifier	26.3	24.23	0.70	11.4	10.75	17.1	17.9
Ash cyclone	(Jin et al., 2009)	kg/s BDG	49.90	46.04	0.70	0.204	0.19	0.31	0.3
Lock-hopper N_2 boost compressor	(Jin et al., 2009)	MW consumed	0.330	0.248	0.67	0.421	0.35	0.44	0.5
Gas clean-up						(M$2003)	(M$2003)	(M$2003)	**(M€2020)**
Syngas cooler	(Jin et al., 2009)	kg/s BDG	49.90	46.04	0.60	22.3	21.26	33.93	35.3
Ceramic filter	(Jin et al., 2009)	kg/s BDG	49.90	46.04	0.65	8.10	7.68	12.26	12.8
ASU						(M$2003)	(M$2003)	(M$2003)	**(M€2020)**
Integrated ASU	(Jin et al., 2009)	kg/s pure O_2	18.00	8.31	0.50	20.3	13.80	17.52	18.3
O_2 compressor	(Jin et al., 2009)	MW consumed	5.30	2.62	0.67	3.60	2.26	2.86	3.0
N_2 compressor	(Jin et al., 2009)	MW consumed	10.80	4.31	0.67	4.40	2.35	2.99	3.1
Power island						(M$2003)	(M$2003)	(M$2003)	**(M€2020)**
Gas turbine[13]	(Pequot Publishing Inc, 2003)							33.24	34.6
HRSG and heat exchangers	(Jin et al., 2009)	MW_{th} heat duty	433	145	1.00	50.3	16.84	25.86	26.9
Steam turbine	(Jin et al., 2009)	Gross MW	190	20	0.67	57.0	12.50	15.88	16.54
									(M€2020)
Additional conventional steam generator[14]	(Restrepo-Valencia and Walter, 2019)	Gross MW		21					15.9
CCUS						(M€2014)	(M€2014)	(M€2014)	**(M€2020)**
Capture unit	(Van der Spek et al., 2017)	kg/s CO_2 captured flow	71.9	39.3	0.6	326	226.8	226.8	241.1
Compression train	(Van der Spek et al., 2017)	kg/s CO_2 compressed flow	71.9	56.9	0.6	44	38.2	38.2	40.6

[10] Original value from reference.

[11] For further details, see note *e* from Table 9 from (JIN; LARSON; CELIK, 2009).

[12] Values in US dollars ($) were converted to Euro using the average exchange rate in 2003 (1.26 $/€), and then updated to 2020 using the Harmonized Index of Consumer Prices (All Items for European Union).

[13] The turn-key price for the GT11N2 gas turbine, in US dollar, was used and then converted into the currency of this study.

[14] The equation taken from reference estimates the turn-key investments in Brazilian currency (R$), as function of installed capacity. Values in $R\$_{2014}$ were updated using the Brazilian general price index and then converted into euro using the exchange rate by the 30/06/2020 (6.15 R$/€).