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Environmental and economic assessment of the co-firing of the coalbagasse mixture in the Colombian sugarcane mills

Evaluación económica y ambiental de la quema conjunta de carbón y bagazo en la industria colombiana de la caña de azúcar

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Abstract

The energy generation is key to any country's development and the threats to energy supply have led the Colombian government to establish national policies that stimulate energy generation projects. In response, this manuscript reports the economic impact and the GHG emission that has been simulated in this study to evaluate the co-firing of the coal-bagasse mixture in the cogeneration systems of the ethanol industry in the Cauca River Valley in Colombia as an opportunity to increase the economic benefits due to the increase of electricity sell to the national grid in the strong dry seasons. This study was performed using the Virtual Sugarcane Biorefinery (VSB) modeling software used for the simulation of agricultural and industrial parameters in integrated alternatives for the sugarcane industry, which was adjusted to the Colombian conditions to allow simulating the current electricity production in the sugarcane mills in the assessed region. The economic assessment of the co-firing process in the cogeneration system demonstrates that this industrial process represents an opportunity to increase the economic benefits of about 26%. However, the coal combustion in the boiler generates about 54% of the total GHG emissions for the consumption of coal, whereas the burning of bagasse corresponds to only 5%.

Keywords: electricity generation; co-firing coal-bagasse; simulation platform; Biorefinery; GHG emissions; ethanol industry.

Resumen

La generación de energía es clave para el desarrollo de cualquier país y las amenazas para el suministro de energía han llevado al gobierno colombiano a establecer políticas nacionales que estimulen los proyectos de generación de energía. En respuesta, este manuscrito informa sobre el impacto económico y la emisión de GEI que se ha simulado en este estudio para evaluar la quema conjunta de carbón y bagazo en los sistemas de cogeneración de la industria del etanol en el Valle del Río Cauca en Colombia como una oportunidad para aumentar los beneficios económicos debido al

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aumento en la venta de electricidad a la red nacional en las fuertes temporadas secas. Este estudio se realizó utilizando el software de modelado Biorrefineria Virtual de Caña de Azúcar (BVC) utilizado para la simulación de parámetros agrícolas e industriales en alternativas integradas para la industria de la caña de azúcar. La BVC que se ajustó a las condiciones colombianas para permitir simular la producción actual de electricidad en los ingenios de caña de azúcar de la región estudiada. La evaluación económica del proceso de quema conjunta en el sistema de cogeneración demuestra que este proceso industrial representa una oportunidad para aumentar los beneficios económicos de alrededor del 26%. Sin embargo, la combustión del carbón en la caldera genera aproximadamente el 54% de las emisiones totales de GEI para el consumo de carbón, mientras que la quema de bagazo corresponde a solo el 5%.

Palabras clave: generación de electricidad; combustión conjunta de carbón y bagazo; plataforma de simulación; biorrefinaria; emisiones de gases de efecto invernadero; industria del etanol.

1. Introduction

In the last years, biofuels have positioned themselves globally as an alternative to fossil fuels, particularly in the transport and power sectors. Worldwide energy policies have encouraged the increment in the use of bioenergy in local energy matrices, as well as they have reduced the fossil fuel dependency and hence avoid being subject to oil price fluctuations. The reduction of GHG emission and the development of agriculture worldwide demand more options for sustainable energy supplies that rely on increasing renewable alternatives. The sustainable production around the biofuel industry has become a real challenge for developing countries. The biofuels in Colombia (ethanol and biodiesel) represent 5% of the road transport sector consumption, corresponding to 59% of the biodiesel use and 41% of ethanol [1]. The biofuels are used in the entire transport sector, in the gasoline with a blend of 8% ethanol (E8), and for diesel with an average blend of 9.2% biodiesel (B9), as is reported by the Regulatory Commission on Energy and Gas [2].

The Cauca River Valley is the main region of ethanol production from sugarcane in Colombia. In 2016, the ethanol production was 456 million of liters, reaching an average of more than 1.25 million liters of ethanol per day, and with an installed capacity of 1,650,000 liters per day [3]. Further, the industrial complex of Bioenergy Company (El Alcaraván), Colombia's largest and newest ethanol plant located in the department of Meta in the region of the Llanos Orientales began the continuous and progressive ethanol production in March of 2017 [4].

All thermal and electric energy required for the industrial process in the Colombian ethanol industry is produced by combined heat and power (CHP) systems, and in some annexed distilleries, the energy generation is through the co-firing of a coal-bagasse mixture [5], [6]. These complementary sources are very important to ensure power supply in the dry season and the El Niño Southern Oscillation (ENSO) period when hydroelectric generation is affected, and because of the low offer of hydraulic energy in this period, it also is obtained a better price for the generated power [7], [8]. In Brazil, the ethanol industry uses only bagasse in the CHP system as the source for the power generation. Also, the reduction in the pre-harvest straw burning currently allows the use of a significant amount of straw as fuel in the CHP systems, which has led to an increase in the surplus electricity production [9], [10].

Mauritius Island has been developing sugar processing systems and associated cogeneration strategies for a long time, under changing global contexts and with various national policy imperatives. Mauritius has been ambitious and very successful in deploying co-firing coal-bagasse cogenerated electricity in the off-crop season, such that it accounted for 17% of the national electricity generation share in 2015 [11], [12].

Accordingly, with the relevant differences in the cogeneration system considered in the Colombian ethanol sector and the Brazilian ethanol industry. Further, the positive experience presented in Mauritius Island with cogeneration process and the participation in the electricity market of the sugarcane mills, in this paper are assessed the annexed distilleries for ethanol production in the traditional agricultural region of the Cauca River Valley, with the objective to improve our understanding of the case study of the co-firing of the coal-bagasse mixture in the CHP systems, evaluating the economic benefits and the environmental impacts. The present study simulates a model of sugarcane mill representing the current technological stage in the Cauca River Valley. The simulation model was adapted to the different amounts of coal used in the CHP system (16.1 to 23.8 kg Mg-1 of sugarcane) and the study case using only bagasse as fuel in the boiler.

This paper is in concordance with the assessment of alternative of clean energy generations that could contribute to achieving the environmental commitment of the country in the COP21 [13].

The results of this research would be helpful to entrepreneurs and policymakers evaluating the contribution of electricity produced from the co-firing of the coal-bagasse mixture in the cogeneration process of the sugarcane mills of the country, and their participation in the electricity market, becoming an important contribution to the value chain.

1.1. The co-firing of coal-bagasse in the CHP system of the Colombian sugarcane mills as the opportunity to increase the electricity production

In Colombia the climate conditions remain relatively stable year round, with dry seasons from December to March and July to August; and intense rain from April to June, and October to November [14] benefitting hydroelectric power as the principal source for electric energy generation. Colombia has more than 15 GW of installed capacity supplied mostly from large hydropower plants [15], [16], contributing to approximately 70% (80% in normal hydrology condition), the remaining 23.4% is supplied by thermal plants (gas and coal, and could be 50% in strong dry seasons), 5% of wood and other energy sources, 0.6% from coal, and natural gas in cogeneration systems, 0.5% biomass in cogeneration systems, and wind power 0.1% [1], [8].

The severe dry seasons due to the variable hydrological cycles and the El Niño Southern Oscillation (ENSO) that reduced precipitation in the country and caused droughts over the past two decades [17] have challenged the country reliance on the hydroelectric source. More recently, in 2015/16, the ENSO became more severe than ever before, decreasing the water supply significantly, approximately 65% of its capacity was diminished [1], [18]. As a result, electricity prices have risen, and thermal power plants were turned on to provide relief for hydropower plants [17], [19]. As a result of this new scenario, the Colombian National Government has seen the need to accelerate the process of diversification of the country's energy matrix. To encourage the interest of investors in participating in new business opportunities that could prompt the energy generation from a renewable source through combined heat and power (CHP) systems, the Colombian national government implemented the Law 1715 of 2014 [20] which regulates the integration of non-conventional renewable energy into the national grid, and in the country's electricity market.

Currently, the bagasse production in Colombia is about 6 Gg per year from the sugar and ethanol production in the Cauca River Valley mills. Also, the carboniferous zone of this region has a total potential of 242.47 Gg of coal resources, in which the bituminous coal is predominant [21]. The co-firing process of the coal-bagasse mixture is an opportunity to increase the electricity generation in the CHP systems in the sugarcane mills. In Colombia, the co-firing of the coal-bagasse mixture in the CHP systems in the sugarcane mills has become very important as a measure to solve the problem of shortage of electric power. Between 2015 and 2016, in the ENSO dry season, the co-firing of coal-bagasse in the sugarcane mills contributed with 51 MW to the energy grid [7]. In 2015 the cogeneration process in the sugarcane mills generated 235 MW, with the possibility to increase the capacity to 337 MW in 2018 due to the government incentives, new energy regulations, and the upgrade of the cogeneration system of the sugarcane mills [3].

In the Cauca River Valley, from the sugarcane bagasse produced annually, 80% is used as fuel in the CHP system, whereas 15 to 20% is used as raw material (fiber) to produce paper and agglomerate in the furniture industry. 500 to 600 Mg of bagasse are sent per day to the paper industry, whereas 180 to 200 Mg of coal are utilized per day in the CHP system of the sugarcane mills [22]. Figure 1 details the coal-bagasse exchange agreement between the paper industry and the sugarcane mills in the Cauca River Valley.

The paper industry (PROPAL S.A.) assesses the quality of the fiber within the bagasse received from the sugarcane mills, determining the bagasse price; also, the movements of the supply, and demand of bagasse, and the opportunity of selling electricity to the grid are relevant in the price formation. The amount of coal to be sent to the mills is calculated with a minimum limit set according to the energy content of the bagasse [23]. It is important to note that there are indirect saving related to the coal-bagasse exchange agreement with the paper industry. The produced bagasse in the sugarcane mills of the Cauca River Valley is the sours of raw material closer to the paper mills decreasing the transport distance, contributing to decreasing the operational cost and the GHG emissions due to the reduction in transport operations compared to the transport of different raw materials (i.e., bamboo, eucalyptus, agroforestry waste) from other region of the country. Further, the fraction rich in fiber that is not used in the paper fabrication, decrease the use of coal in the CHP system of the paper mill and contribute decreasing the GHG emissions.

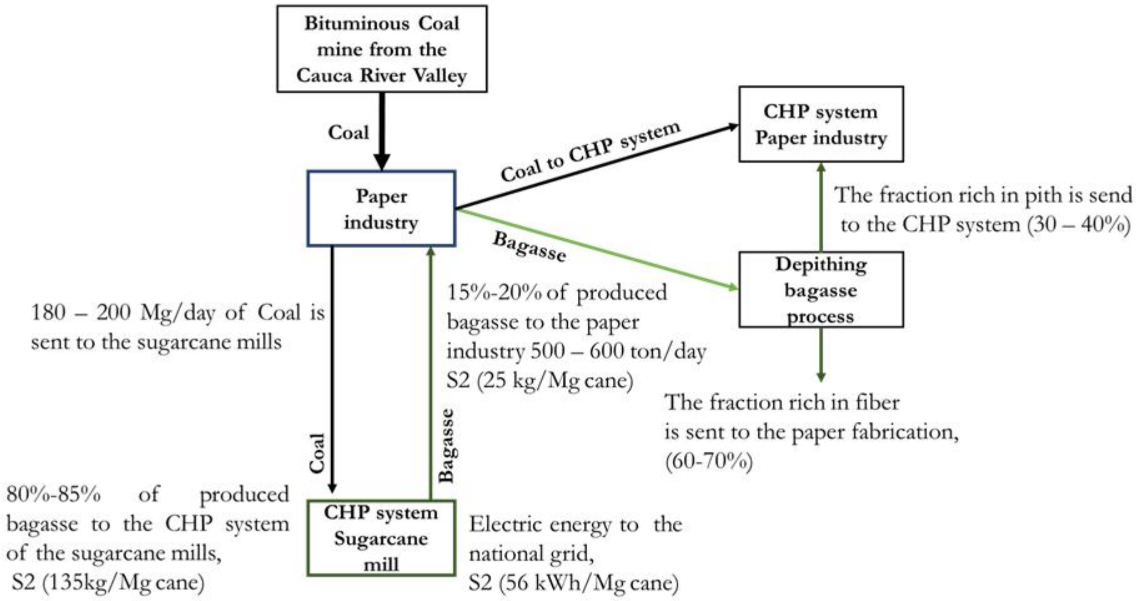

Figure 1. Scheme of coal – bagasse exchange agreement between the paper industry and the sugarcane mills (Becerra-Quiroz, Buitrago-Coca, and Pinto-Baquero 2016; Ingenio Incauca 2016; Ingenio Providencia 2016).

2. Methodology

This study was performed using the Virtual Sugarcane Biorefinery (VSB) developed by the Brazilian Bioethanol Science and Technology Laboratory (CTBE) [24], [25]. The VSB is a structure that comprises computer simulation platforms with computational tools for economic, social and environmental evaluation. The VSB can represent different sugarcane biorefinery routes and alternatives comprising all the stages of the sugarcane chain: agricultural, transport, industrial process, and management of products disposal. An important feature of the VSB is its flexibility since it is possible to adjust several parameters depending on the type of bioenergy chain scenario. The agricultural and industrial simulations of this study were based on Brazilian sugarcane mills, where the necessary adaptations were carried in order to better represent the current conditions of the sugarcane and ethanol production and the usual industrial waste treatment in Colombia. Also, the technical, economic and environmental parameters considered, were adjusted to the VSB.

The current sugarcane and ethanol production and the average coal-bagasse consumption in the annexed distilleries of the Cauca River Valley region in Colombia were the foundation to represent the evaluated scenarios. Table 1 summarizes the basic agricultural parameters considered in this study to represent the sugarcane production in Colombia. Further, presents the industrial parameters considered in this study to represent the industrial process and the main products obtained in the simulated biorefineries. Table 2 presents the main parameters, considered in the simulated CHP system for the representation of the cofiring of coal-bagasse in the evaluated simulations. Moreover, Table 3 summarizes the main differences between the fuels (coal and bagasse). For these simulations, a combustion efficiency of the coal-bagasse mixture of 82% was considered accordingly with the value reported in the CHP system of the Ingenio Providencia [7]. For the simulations, different amounts of coal were considered to compare electricity production, economic revenue, and environmental impacts. Increasing amounts of coal from 16.1 to 23.8 kg of coal per Mg of sugarcane (S2 to S5) was used in the CHP system, accordingly with the average of coal used in the cogeneration systems of the mills in the Cauca River Valley (Becerra-Quiroz et al., 2016). Also, the case without the use of coal in the cogeneration system was considered as the baseline for comparison (S1). The evaluated scenarios consider a milling capacity of 3 Gg of sugarcane per year, an ethanol production of 26.6 liters per Mg of sugarcane, 98.1 kg of sugar per Mg of sugarcane, and a bagasse production of 0.95 Gg per year (approximately 317 kg per Mg of sugarcane (wet basis)). The amount of bagasse sent to the paper industry was considered as 15% of the total amount of bagasse that is produced, corresponding to 74,000 Mg of bagasse per year (24.7 kg (dry basis) per Mg of sugarcane).

Table 1. Summary of the main parameters adopted in the simulations to represent the agricultural and the industrial stage of sugarcane processing in evaluated scenarios

Agricultural parameters	**S1, S2, S3, S4, S5**
Average sugarcane yield (Mg/ha.yr)	120
Total area of the mill (sugarcane ha)	25,424
Planting area (ha)	5,085
Average transport distance (km)	25
Semi-mechanized planting	100
Mechanized planting (%)	-
Sugarcane seeds (Mg/ha)	10
Total mechanized harvest (%)	51
Total manual harvesting (%)	49
Irrigation water (m^3/ha.y)	7,529
NPK (fertilizers application)	
N (kg/ha.yr)	54.0
P_2O_5 (kg/ha.yr)	4.2
K_2O (kg/ha.yr)	46.4
Industrial Parameter	
Type of distillery	Annexed distillery
Milling capacity (Gg/y)	3
Effective operation (days)	330
Ethanol production (l/Mg $_{cane}$)	26.6
Sugar production (kg/ Mg $_{cane}$)	98.1
Raw material (ethanol production)	Final and B molasses
Concentrated vinasse	45° Brix
Power drives (juice extraction stage)	Electric
CHP system (technology)	
Bagasse reserve (start-up) (%)	3.5%*
Energy demand (power drives) (kWh/ Mg $_{cane}$)	30
Energy demand (irrigation) (kWh/ Mg $_{cane}$)	13.8
Boiler pressure (bar)	65
Boilers efficiency (%) (LHV base)	82
Temperature of exhaust gas (°C)	160.0
Generated steam temperature (°C)	478.0
Condensing turbine use	No
Isentropic efficiency of the turbines (%)	83
Process steam pressure (bar)	2.5

Table 2. Main inputs considered in the simulated CHP system of the evaluated scenarios (dry basis)

Parameter	**Coal-bagasse mixture**				
	S1	S2	S3	S4	S5
Inputs to the mill					
Coal to the boiler (kg/Mg $_{cane}$)	-	16.1	18.5	21.1	23.8
Bagasse to the boiler (kg/Mg $_{cane}$)	157. 2	132. 5	132. 5	132. 5	132. 5
Outputs from the mill					
Bagasse to the paper industry (kg/Mg cane)	0	24.7	24.7	24.7	24.7
Electricity (Industrial process) (kWh/Mg $_{cane}$)	46.8	46.8	46.8	46.8	46.8
Electricity (sell to the grid) (kWh/Mg cane)	55.6	56.0	57.6	59.3	61.1
Total electricity production (kWh/Mg $_{cane}$)	102. 6	102. 7	104. 4	104. 1	107. 8

Table 3. Composition of coal and bagasse considered in the CHP systems (dry base) of the sugarcane mill in the Cauca River Valle in Colombia (UPME 2005; Castillo, 2009)

Ultimate analysis (%)	**Coal**	**Bagasse**
C	63.7	24.7
H	4.8	3.0
O	8.8	23.1
S	0.8	0.1
N	1.1	-
H_2O	-	47.0
Ashes	20.9	2.1
HHV (MJ/kg)	26.1	18.5-
LHV (MJ/kg)	31.8	7.5

2.1. The agricultural stage simulation

The feedstock production system, considering the sugarcane management in the different scenarios, were modeled using CanaSoft model, included in the Virtual Sugarcane Biorefinery (VSB). This model is based on interconnected spreadsheets and integrates several calculation modules and databases. It is based on the definition of the main parameters that characterize a sugarcane production system (e.g., yield, operational efficiencies, pre-planting operations, harvesting systems, fertilizer doses, mechanical operations, and transport distances, among other factors). These parameters are considered for the life cycle inventory calculation and for the economic assessment. Both economic and inventory calculations are linked to an agricultural database which involves the information about all agricultural operations used in sugarcane production such as agricultural performance parameters, types of harvesters, tractor and implements, as well as their weight, costs, diesel consumption, annual use, lifespan, and depreciation, among other parameters. The composition of the sugarcane considered in the simulation correspond to water (70.3%), sucrose (14%), reducing sugars (0.6%), fibers of 13.2% (corresponding to a cellulose content of 6.2%, hemicellulose 3.7%, and lignin 3.3%), and others such as organic acids and minerals (2.1%) [26], [27]. The composition of the bagasse (in wet basis) used in the compost production model corresponds to water content of (47.9%), sucrose (1.1%), reducing sugars (0.1%), fibers of 49.1% (corresponding to a cellulose content of 26.4%, hemicellulose 13.9%, and lignin 12.5%), and others, such as, organic acids and minerals (1.2%) [28].

In the agricultural stage for the scenarios, the production, and harvesting operation was considered to run all year round (330 days). The irrigation process was assumed through the open channel irrigation system and water consumption of approximately 1500 m3/ha that was carried out five times per year. The irrigation area represents 95% of the total area, and the water used was 50% surface water, and 50% groundwater. Moreover, the manual harvesting index of 49% was considered with the previous burning of sugarcane straw, and a mechanical harvesting of 51%. The ethanol production was simulated using molasses as raw material, and also the vinasse concentration process was considered, with vinasse reaching a 45º Brix accordingly to CUE, (2012).

2.2. The industrial stage simulation

Regarding the industrial conversion phase, mass and energy balances, the industrial configurations were obtained through computer simulations of the industrial scenarios using the Aspen Plus® software included in the VSB.

In the simulation process, were considered updated operational and process parameters of the annexed plants and autonomous distilleries in Colombia. The calculated mass and energy balances helped in modeling the industrial life cycle inventory, including the identification of the main products (sugar, ethanol, and electricity), as well as the most significant industrial byproducts (bagasse, filter cake, vinasse, and ashes) and the greenhouse gas (GHG) emissions. The different amounts of coal in the coal-bagasse mixture that were considered in the simulations was equivalent to the average of coal consumption in the main distilleries of the region (Ingenio Incauca, Ingenio Providencia, Ingenio Mayaguez) [16]. The selected scenarios in this study are based on the industrial process described in Figure 2, which presents the process flowsheet related to the current ethanol production in the Cauca River Valley mill.

2.3. Economic benefits related to the co-firing of the coal-bagasse mixture in the CHP systems of the Colombian sugarcane industry

Production of anhydrous ethanol, sugar, electricity, byproducts, and GHG emissions were obtained for each scenario based on the results of computer simulations of the industrial process using the Aspen Plus® software included in the VSB. Sugarcane total production cost for the several evaluated scenarios was calculated using the economic module of CanaSoft model in the VSB framework.

The economic assessment was based on a cash-flow analysis for each scenario, taking into account the investment and all expenses and revenues that came from technical parameters obtained through the simulation of the industrial process (process of mass and energy balances), and from historical data observed over recent decades for sugar, ethanol, and electricity production costs, and market prices. To compare the economic viability of the scenarios, the internal rate of return (IRR) and net present value (NPV) were calculated to analyze their economic performance. The VSB usually allocates the total cost and its elements among the biorefinery products according to their share in the total revenues.

This approach is necessary to determine the cost breakdown of ethanol, sugar, and electricity production.
For the economic assessment, the agricultural and the industrial dataset for the evaluated scenarios were calculated using one Mg of sugarcane processed as the functional unit. Furthermore, the lifetime of the industrial plant includes 2 years of construction and start-up plus 25 years of full production capacity (project lifetime). This was considered, and the value of the plant at the end of the project was assumed to be zero. The sugar, ethanol, and electricity market prices were assumed to be US$ 0.44 per kg of sugar [29], US$ 0.85 per liter of ethanol [30], and US$50.9 per MWh of electricity [31]. The land cost considered was accordingly to the average land cost in Colombia of US$450 per ha considered in the average historical data from 2006 to 2014. The minimum

attractive rate of return (MARR) was 15.3% calculated through the Capital Asset Pricing Model (CAPM) [32], [33]. The exchange rate was calculated as COP/US$ = 2049.3; R$/US$ = 2.65. The period of historical data to calculate the product prices was considered from 2006 to 2014. The total production costs are obtained by summing operating and capital expenses. In the case of ethanol production, the cost per liter would be the yearly total cost divided by the number of liters of ethanol produced over the year.

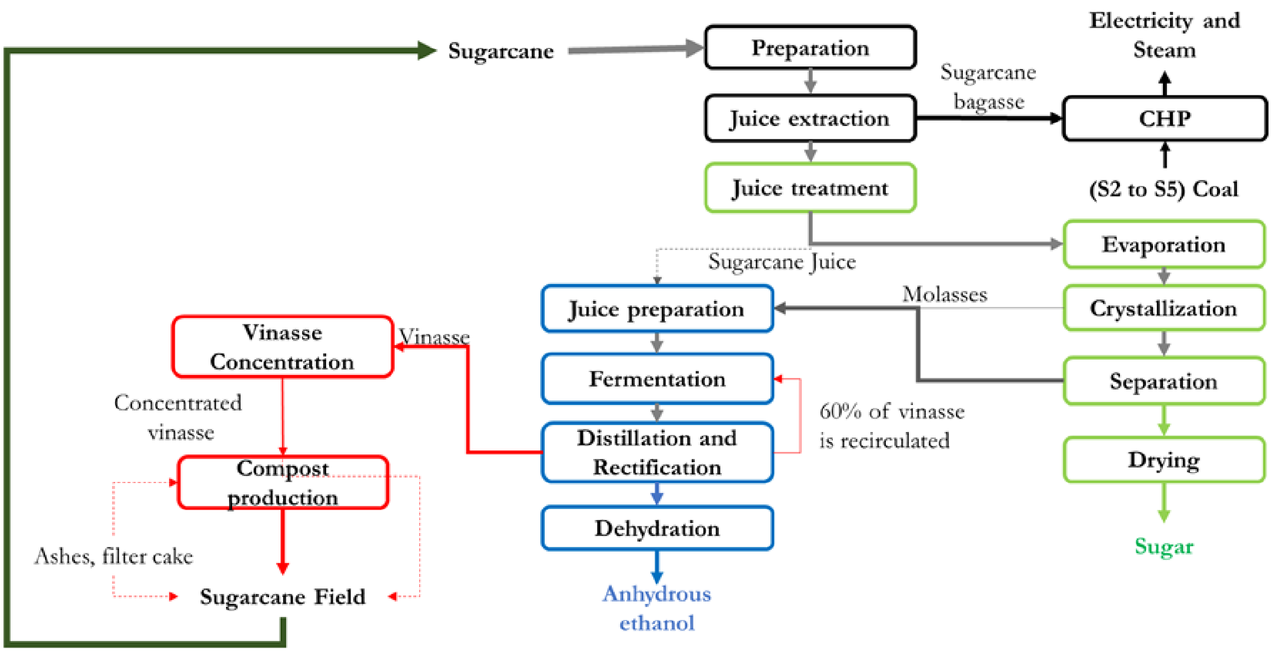

Figure 2. Process flowsheet of the current annexed distillery in Cauca River Valley, ethanol production (blue), sugar production (green), cogeneration system (black), and waste treatment unit (red). (CENICAÑA 2015; CUE 2012).

2.4. Environmental impacts related to the cofiring of the coal-bagasse mixture in the CHP systems of the Colombian sugarcane industry

The evaluation of GHG emissions associated with the ethanol production from sugarcane in Colombia within the VSB framework was performed using the Life Cycle Assessment methodology (LCA). The LCA is a wellknown method for determining the environmental impact of a product, process, or activity, by the identification and quantification of energy and materials used and waste released during its entire life cycle [34]. According to LCA methodology, the allocation is required for multi-output processes. In this study, the criteria used for the different outputs of the industrial process were the economic allocation among the biorefinery products according to their share in the total revenues. The development of this study is a __cradle to gate‘‘ analysis with the functional unit being a liter of anhydrous ethanol, covering a broad range of environmental aspects from GHG emissions. It evaluates all resources used and emissions released (to the air, soil, and water) from the extraction of raw materials through manufacturing, logistics, and final products. The ReCiPe Midpoint Impact Assessment method [35] has been used in the environmental impact assessment in the VSB framework to assess impacts in terms of GHG emissions measured in kg of CO2eq. Impact assessment examines the environmental burdens of the emissions and the resources used and quantified in the inventory analysis.

To assess the environmental impacts of the combustion process in the CHP system, gaseous emissions generated by coal and bagasse combustions were utilized as described in EPA (2009). The GHG emissions from the bagasse production were estimated based on the emissions of the sugarcane production, which were calculated using the CanaSoft model.

3. Results and Discussions

3.1. Economic results related to the co-firing coal-bagasse in the Annexed distilleries in Colombia

The calculated sugarcane cost in the scenarios representing current production of an annexed distillery in the Cauca River Valley is similar to the sugarcane cost per hectare reported in the literature of US$2,248 [36]

For the evaluated distilleries in the Cauca River Valley, the agricultural operations (machinery, maintenance, and diesel cost) and the land cost corresponds to more than 60% of sugarcane production cost for the evaluated scenarios. The irrigation process corresponds to 15% of the sugarcane cost.

In the output analysis of the simulated annexed distilleries, it is possible to observe that the sugar production of 98.1 corresponds to the industrial average sugar production in the region of 70 – 93 kg per Mg of sugarcane [37]. The ethanol production of 26.6 liters per Mg of sugarcane corresponds to the average production in the region of 15 to 22 liter per Mg of sugarcane. The electricity production per Mg of sugarcane to sell to the grid obtained for the simulated scenarios, among 51.1 to 61.1 corresponds to the industrial average production in this region (24 to 70 kWh/Mg cane). The economic analysis of the co-firing of the coalbagasse mixture in the CHP system was performed to assess the opportunity of increasing the electricity production to be sold to the national grid by the use of different amounts of coal in the CHP system. Regarding the economic comparison, a sugarcane mill without the use of coal (S1) was considered as the baseline. The price of electricity was set at US$50.6 per MWh [16], and for this study, a value of US$50.86 per Mg of bagasse sent to the paper industry was considered, this value corresponds to the opportunity cost for the exchange of coal and bagasse between the paper industry and the ethanol sector. Table 4 details the main economic revenues related to the different amounts of coal considered in the simulation. Further, are presented the total investment estimated for the sugarcane mills assessed, and the results, referring to the IRR and the NPV of the selected scenarios.

The opportunity of increasing the electricity production by the process of the co-firing coal-bagasse mixture could increase the annual electricity revenues by 16% for a consumption of 16.1 kg of coal per Mg of sugarcane (4000 Mg of coal per month). Also, an increase of 23% can be seen for the use of 23.8 kg of coal per Mg of sugarcane (6000 Mg of coal per month). Accordingly, with the technical and economic assessment, the simulation representing the average annexed distillery of the Cauca River Valley presents values of 17 MW (S2, 16.1 kg/Mg cane) to 25MW (S5, 23.8 kg/Mg cane) sold to the grid. Finally, the increase of consumption of coal in the CHP system of the sugarcane mill shows the opportunity of increasing the Internal Rate of Return (IRR) mainly due to the increase in the electricity generation and the lower initial investment compared to the case without coal consumption. It is important to note that the increase of use of coal is only in the years with a strong dry season or in the periods of the ENSO. In the rain season, the electricity prices are low, and the co-firing process is less interesting, and the coal use decrease. Is important to highlight that the Colombian sugarcane mills continually are improving the cogeneration system through update the boiler specifications and the equipment modernization to increase the electricity generation, decrease the GHG emissions, and the particulate matter released in the cogeneration process [22].

Table 4 Economic inputs and outputs of the coalbagasse mixture co-fired in the simulated CHP

Parameter	**Coal-bagasse mixture**				
	S1	S2	S3	S4	S5
Sugarcane cost (US$/Mg $_{cane}$)	18.6	18.6	18.6	18.6	18.6
Sugarcane cost (US$/ha. yr)	2203 ,7	2203 ,7	2203 ,7	2203 ,7	2203 ,7
IRR (% per year)	22.1	24.3	24.3	23.4	24.4
NPV (US$ million)	148. 7	182. 2	183. 6	184. 9	185. 3
Sugar cost (US$/kg)	0.32	0.32	0.32	0.32	0.32
Ethanol cost (US$/L)	0.62	0.62	0.62	0.62	0.62
Electricity cost (US$/MWh)	36.2	36.3	36.4	36.5	36.6
Total investment estimate (US$ million)	314. 2	283. 8	283. 8	283. 8	283. 8
Economic inputs and outputs					
Annual electricity revenue (electricity sold to the grid) (US$ million)	7.1	8.5	8.7	9.0	9.3
Annual cost of bituminous coal (US$ million)	-	2.5	2.8	3.2	3.6
Annual revenue for surplus bagasse (paper industry) (US$ million)	-	3.8	3.8	3.8	3.8
Net benefit (US$ million)	7.1	9.8	9.7	9.6	9.5

3.2. GHG emissions related to the co-firing of the coal-bagasse mixtures in the Annexed distilleries in Colombia

Environmental impact assessment related to the greenhouse gas (GHG) emissions of the sugarcane production, industrial production (sugar, and ethanol), and the co-firing of the coal-bagasse mixture in the CHP system to produce electricity were analyzed using a cradle to gate Life Cycle Assessment (LCA).

Sugarcane production (bagasse production) impacts are mainly related to fertilizer use, diesel consumption in agricultural operations, sugarcane transport, industrial waste treatment, and transport to the field, and preharvesting sugarcane burning Figure 3 shows the GHG emissions in CO_2eq per liter of ethanol, corresponding to the production and burning of only bagasse (S1), and different amounts of coal in the co-firing coal-bagasse mixture of 16.1 to of 23.8 kg of coal per Mg of sugarcane (S2 to S5).

The coal combustion in the boiler generates 0.7 kg of CO_2eq per liter of ethanol, more than 54% of the total GHG emissions for the production and consumption of 16.1 kg of coal per Mg of sugarcane (4000 Mg/month) in S2, whereas the burning of bagasse corresponds to only 5% of the total GHG emission. For the evaluated model with consumption of 23.8 kg of coal per Mg of sugarcane (6000 Mg/month) in S5, the GHG emissions of 0.9 kg of CO_2eq per liter of ethanol from the coal combustion represent more than 64% of the total GHG emissions. The GHG emissions from the ethanol production in the case of coal consumption of 16.1 kg per Mg of sugarcane S2 were of 1.31 kgCO_2eq per liter of ethanol, representing a reduction of 0.38 kgCO_2eq comparing with the GHG emissions from the ethanol production in USA of 1.7 kgCO_2eq per liter [38]. In Figure 4 it is possible to note the potential reduction of GHG emission of the ethanol production in the evaluated scenarios of the co-firing of the coal-bagasse mixture when compared to the emissions of the gasoline from the United States. comparing with the GHG emissions from the ethanol production in the USA of 1.7 kgCO_2eq per liter [38].

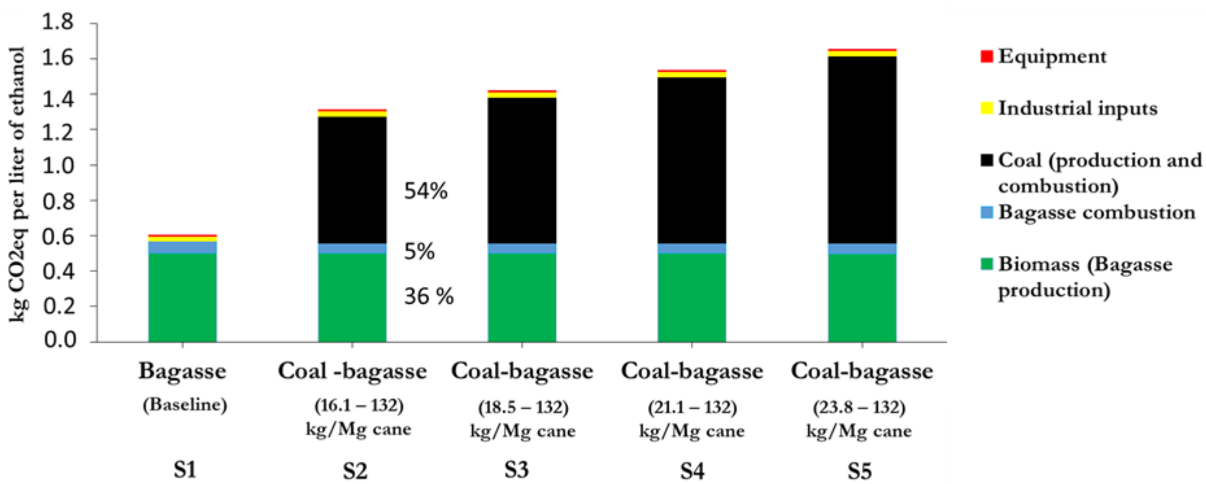

Figure 3. Comparison of the GHG emissions of different coal-bagasse mixture co-firing in the CHP system, and the burning process of 100% bagasse.

In Figure 4 it is possible to note the potential reduction of GHG emission of the ethanol production in the evaluated scenarios of the co-firing of the coal-bagasse mixture when compared to the emissions of the gasoline from the United States. To compare the reduction of GHG emissions the complete LCA (well to wheel) was considered, the transport and use of ethanol as 2.18 g of CO_2eq per MJ [37] was assumed and added to the ethanol production. The GHG emissions from the production and use of gasoline from United States of 93g of CO_2eq per MJ [39] is the reference value widely accepted for the determination of reduction in GHG emissions [39].

It is important to highlight that the ethanol produced in the Cauca River Valley does not qualify as an advanced biofuel by the EPA criteria [40] of 50% reduction of the GHG emissions. Also, it does not meet the requirements of the European Parliament [41]. The potential reduction in the GHG emissions by the reduction of coal use would allow the qualification as advanced biofuel with more than 50% reduction in GHG emission. In the case of the baseline where only bagasse is used in the CHP system (S1), the reduction in the GHG emissions allow the D5 (D correspond to ethanol, and 5 correspond to the classification as advanced fuel) classification from EPA, as well as it reaches the EU requirements.

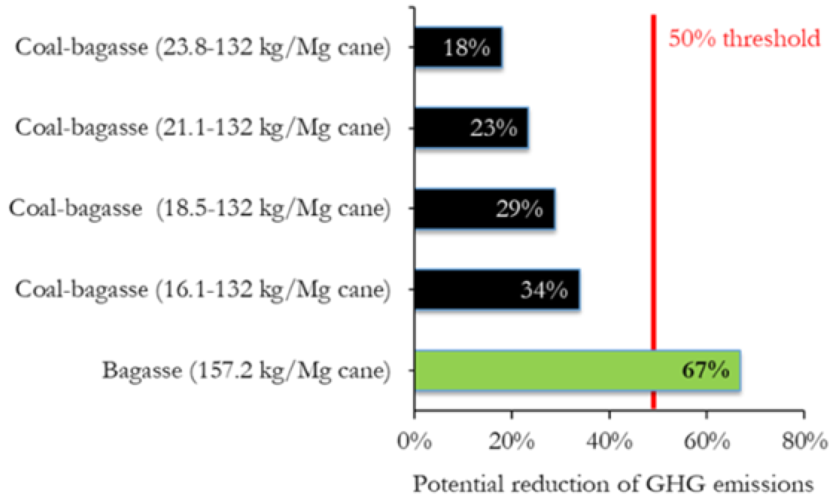

Figure 4. Reduction of GHG emissions in the evaluated scenarios compared with the USA gasoline emissions.

4. Conclusions

The present study had the objective to assess the cofiring of the coal-bagasse mixture in the CHP systems of the ethanol industry in the Cauca River Valley region in Colombia and evaluate the electricity generation and possible economic benefits and the environmental impacts related with the cogeneration process. The use of the VSB allowed performing an economic and environmental assessment for the proposed scenarios in this study.

The simulations with co-firing coal-bagasse mixtures show high environmental impacts by the account of the GHG emissions from the coal production and combustion, compared with the simulation without the coal burning process (100% bagasse). The sugarcane mill simulated in this study could sell 17 to 25 MW to the central grid, this value is similar to the one expected by the sugarcane mills od the Cauca River Valley, of 15MW, by 2018. In conclusion, the co-firing of coalbagasse consumption in the CHP system of the ethanol industry in Colombia is an important opportunity to increase the economic benefits due to the increase in the electricity generation to sell to the national grid in the dry season, and in the ENSO period.

It is also important to assess the interest of the sugarcane mills in encouraging the expansion of the ethanol production for the international market, since the reduction of coal use would allow the qualification as advanced biofuels, according to the EPA criteria. The intention of upgrading the CHP systems of the sugarcane mills in the Cauca River Valley and the cofiring of the coal-bagasse mixture is of fundamental importance for the business opportunity of the ethanol industry in Colombia, increasing the capacity of cogeneration, and the reduction of the GHG emissions.

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References

[1] UPME, “Informe mensual de variables de generación y del mercado eléctrico colombiano – enero de 2015 subdirección de energía eléctrica – grupo de generación”, Minist. Minas y Energía, zenb. 69, or. 1–16, 2015.

[2] CREG, “Estudio sobre mercados internacionales de biocombustibles con é nfasis en alcohol anhidro y biodiésel a partir de palma africana. Informe final Comisi ón de regulación de Energ í a y gas 24 de agosto de 2015”, Bogota, 2015.

[3] ASOCAÑA, “Aspectps Generales del Sector Azucarero Colombiano 2015-2016”, 2016.

[4] BIOENERGY, “Producido, Bioenergy Noticias: Más de 15 millones de litros de etanol”, BIOENERGY, 2017. [Sarean]. Available at:

http://www.bioenergy.com.co/SitePages/Noticia.aspx?IdElemento=38.

[5] Ingenio Providencia, "Procesos Ingenio Providencia", Cali, 2016.

[6] Ingenio Incauca, "Procesos del Ingenio Incauca", Cali, 2016.

[7] J. M. Rincón, M. A. Vera, P. Guevara, eta S. Duarte, "Cofiring in sugar mills industry in Colombia," VGB Power Tech, or. 2015–2018, 2017.

[8] UPME, "Capacidad Instalada De Autogeneración y Cogeneración En Sector De Industria, Petróleo, Comercio Y Público Del País Informe Final Presentado A: Unidad De Planeación Minero Energética-UPME", Unidad Planeación Min. Energética, or. 278, 2014.

[9] M. O. S. Dias, M. P. Da Cunha, R. MacIel Filho, A. Bonomi, C. D. F. Jesus, eta C. E. V Rossell, "Simulation of integrated first and second generation bioethanol production from sugarcane: Comparison between different biomass pretreatment methods", *J. Ind. Microbiol. Biotechnol*., libk. 38, zenb. 8, or. 955– 966, 2011.

[10] T. F. Cardoso et al., "Technical and economic assessment of trash recovery in the sugarcane bioenergy production system", Sci. Agric., libk. 70, zenb. 5, or. 353–360, 2013.

[11] L. S. To, V. Seebaluck, eta M. Leach, "Future energy transitions for bagasse cogeneration: Lessons from multi-level and policy innovations in Mauritius", Energy Res. Soc. Sci., zenb. October, or. 0–1, 2017.

[12] M. K. Chauhan, Varun, S. Chaudhary, S. Kumar, eta Samar, "Life cycle assessment of sugar industry: A review," *Renew. Sustain. Energy Rev*., libk. 15, zenb. 7, or. 3445–3453, 2011.

[13] INDC, "Intended Nationally Determined Contribution. Colombia", Bogotá, 2015.

[14] UPME, Integración de las energías renovables no convencionales en Colombia. Bogotá, 2015.

[15] PROCOLOMBIA, "Electric Power in Colombia. Power Generation – 2015," 2015.

[16] XM, "Informe Seguimiento Cogeneradores Resolución CREG 05 de 2010", 2015.

[17] J. R. Paredes eta J. J. Ramírez, "Variable Renewable Energies and Their Contribution to Energy Security: Complementarity in Colombia," 2017.

[18] COLOMBIA REPORTS, "Colombia reports: fact sheets". Bogota, or. 4, 2015.

[19] BUSINESS WIRE, "Fitch:El Nino Testing Colombia Electricity Regulatory Framework," or. 1, 2015.

[20] Congreso De Colombia, "LEY 1715 mayo de 2014", Pres. la Repub., zenb. May, or. 26, 2014.

[21] UPME, "El Carbón Colombiano. Fuente de Energía para el mundo", 2005.

[22] A. Paredes eta L. Bermúdez, «Eficiencia energética enfocada al medio ambiente en el Ingenio Providencia S.A.», Tecnicaña, libk. 21, or. 607–611, 2009.

[23] S. Arango, A. Yoshioka, eta V. Gutiérrez, "Análisis del ambiente competitivo del Cluester Bioindustrial del Azucar en el Valle Geográfico del río Cauca", Cali, 2011.

[24] A. Bonomi, O. Cavalett, M. P. Da Cunha, eta M. Lima, Virtual Biorefinery, "An Optimization Strategy for Renewable Carbon Valorization. Springer International Publishing, 2016.

[25] O. Cavalett et al., "Sugarcane processing for ethanol and sugar in Brazil", Environ. Dev., libk. 15, or. 35–51, 2015.

[26] CENICAÑA, "Informe anual 2014», Cent. Investig. la Caña Azúcar Colomb., or. 1–164, 2014.

[27] CENICAÑA, "CENICAÑA - Proceso de obtención de azúcar y etanol", or. 1, 2015.

[28] A. Milanez et al., "De promessa a realidade : como o etanol celulósico pode revolucionar a indústria da cana-de-açúcar - uma avaliação do potencial competitivo e sugestões de política pública", 2015.

[29] J. Moncada, M. M. El-Halwagi, eta C. A. Cardona, "Techno-economic analysis for a sugarcane biorefinery: Colombian case», Bioresour. Technol., libk.

135, or. 533–543, 2013.

[30] FEDEBIOCOMBUCTIBLES, «Fedebiocombustibles», Precios de Alcohol Carburante (ethanol), 2017. [Sarean]. Available at: http://www.fedebiocombustibles.com/v3/estadisticaprecios-titulo-Alcohol_Carburante_(Etanol).htm. [Eskuratua: 19-apr-2018].

[31] XM, «Informe Integrado 2015», 2015.

[32] A. Damodaran, «Estimating discount rates», in Damodaran on Valuation: Security Analysis for Investment and Corporate Finance, Second Edition, 2012, or. 1–66.

[33] J. H. Sánchez, «The discount rate in emerging countries-application of the Colombian case», Rev. EAN, zenb. 69, or. 120–134, 2010.

[34] ISO, «ISO 14041:1998 - Environmental management — Life cycle assessment — Goal and scope definition — Inventory analysis», Int. Organ. Stand., libk. 3, zenb. 6, or. 22, 1998.

[35] M. Goedkoop, R. Heijungs, M. Huijbregts, A. De Schryver, J. Struijs, eta R. Van Zelm, «ReCiPe 2008», 2009.

[36] COLOMBIA.MINAGRICULTURA, «Cadena Productiva de la Caña de Azúcar». 2014.

[37] Consorcio CUE, «Estudio ACV – Impacto Ambiental», in Evaluación del ciclo de vida de la cadena de producción de biocombustibles en Colombia, libk. II, Medellin: Banco Interamericano de Desarrollo (BID) – Ministerio de Minas y Energía, 2012, or. 203.

[38] BNDES and CGEE, Bioetanol de cana-deaçúcar : energia para o desenvolvimento sustentável, zenb. 1. 2008.

[39] A. Farrel eta D. Sperling, A Low-Carbon Fuel Standard for California, libk. 38. 2010.

[40] EPA, «EPA Lifecycle Analysis of Greenhouse Gas Emissions from Renewable Fuels», Regul. Announc., libk. 211, zenb. February, or. 4, 2010.

[41] European Parliament, «Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009», Off. J. Eur. Union, libk. 140, zenb. 16, or. 16–62, 2009.

[42] A. Becerra-Quiroz, A. Buitrago-Coca, eta P. Pinto-Baquero, «Sostenibilidad del aprovechamiento del bagazo de caña de azúcar en el Valle del Cauca, Colombia», Ing. Solidar., libk. 12, zenb. 20, or. 133, 2016.

[43] CUE, Evaluación del ciclo de vida de la cadena de producción de biocombustibles en Colombia. Capitulo II : Estudio ACV – Impacto Ambiental, libk. II. 2012, or. 203.