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Techno-Economic Feasibility of Steam and Electric Power Generation from the Gasification of Several Biomass in a Sugarcane Mill

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Abstract

The present work investigated the techno-economic feasibility of using gasification as an alternative to direct combustion to generate steam and electric power generation in a sugarcane mill using different types of solid biofuels. Two cogeneration scenarios were analyzed: scenario 1 (S1), using a boiler and steam turbines only, while scenario 2 (S2) uses gas and steam turbines. It was found that for a solid biofuel cost of 8 US $/ton, the economic results between types of biomass are similar, but at a higher solid biofuel cost, the cost of energy production is lower in S2 when compared to S1. The cost of generated power in S1 using sugarcane bagasse (0.091 US $/kWh) is higher than the cost considered for grid electricity (0.077 US$/kWh), while in S2 is lower (0.063 US$/kWh); therefore, electricity might be exported to the grid at a competitive price in S2. In both scenarios, the greatest contribution to the total annual costs comes from the investment required by about 83%. In the case of the other biofuels, such as cladodes, oil brunches, and coffee pulp, the cost obtained is less than 0.077 US$/kWh for all cases in both scenarios, except for the tender cladodes in S1, mainly due to its higher moisture content. The systems studied in S2 using oil palm empty brunches as complementary solid biofuel in the sugar mill are recommended for year-round bioenergy production.

Keywords Sugarcane mills · Cogeneration · Gasification · Sugarcane bagasse · Coffee pulp

Introduction

Using fossil fuels to produce energy has intensified climate change. This has motivated the development of renewable energy sources [1, 2], such as biomass and biowaste [3, 4] following a circular economy model for energy and high added value material production [5]. Besides, the use of biomass can provide economic savings, increase energy security, and promote local and regional economic development [6].

Recovering energy from biomass or organic solid waste requires biochemical, chemical, and/or thermochemical processes. Biomass combustion is the oldest and more widely used process for industrial applications [6–8], but it represents issues of particulate matter emissions restricted by environmental regulations. Cultivating energy crops is conducive to increased soil erosion and organic carbon losses [4], while using non-primary crop biomass (such as agroindustrial residues) can reduce emissions and residues generation but feasibility needs to be evaluated. Advanced biofuels can be obtained from other thermochemical processes [9]. Gasification is one of the most prominent thermochemical conversion processes gaining interest [6, 7]. In addition to producing syngas from biomass for subsequent biofuel synthesis, gasification typically achieves superior efficiency for electricity generation compared to direct combustion or anaerobic digestion. Using gas engines or fuel cells, electricity can easily be generated from syngas with existing or marginally modified infrastructure [10].

The present work undertakes a techno-economic analysis of gasification of sugarcane bagasse for cogeneration in a sugarcane mill during the time sugarcane is harvested and processed (called *zafra* in Spanish) and its comparison with the gasification of other biomasses such as oil palm empty fruit bunches (OPEFB), agave bagasse, tender cladodes, and coffee pulp. A few works report the technical potential of these biomasses for gasification-based energy generation. For example, agave bagasse [11], coffee pulp, and tender cladodes have been characterized and investigated using thermogravimetric analysis [12]. The gasification of sugarcane bagasse and OPEFB has been studied and modeled [13–19],

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representing efforts to optimize operating conditions. However, the detailed simulation and techno-economic analysis are necessary for an assessment of economic viability in the context of a sugar cane mill. To the best of our knowledge, there is not any other paper in the literature that investigates the use of different biomass for year-round operation for in the context of a sugar mill operation. Different types of biomass feedstock are tested, in addition to the sugarcane bagasse, because the bagasse is produced for just 4 months during the year; therefore, other biomass sources locally available to a sugar mill can be used. This paper carries out such an assessment with a view for operating the bioenergy system during the whole year by the sugar cane mill. The study was focused on biomass gasification and using the syngas to produce steam and electricity in a boiler and steam turbine (scenario 1) or using a gas turbine (scenario 2).

Materials and Methods

Process Simulator

This paper considered the capital and operation cost for the implementation of a cogeneration system based on the gasification of sugarcane bagasse, or other locally available biomass, instead of the usual combustion system located in the sugarcane mill called Central Motzorongo in Veracruz State, Mexico. First, the data of biomass was collected (Table 1) in addition to process information and energy requirements of the sugarcane mill, followed by the conceptual engineering in the process simulator SuperPro Designer® (Intelligen) for the gasification of biomass. Then, the techno-economic analysis was performed. This study used the SuperPro Designer simulation software (Version 9.5), because it was designed specifically to model bioprocesses and it allows a built-in economics analysis for estimating operating and capital costs [20], which was a key aspect of this study. In the case of missing data, some estimations were performed based on data reported in similar processes in the literature (Table 2). The simulation flowsheet of the systems analyzed is shown in Figs. 1, 2, and 3.

Biomass Composition

Biomass composition used in this study corresponds to typical biomass present in regions of Mexico where the 51 sugarcane mills are installed (Table 1) [21, 22]. The corresponding composition was entered into the gasifier model in SuperPro Designer for each of the biomass cases. These sugarcane mills are distributed in 22 states in the country and the States of Veracruz and Jalisco have 22 and 6 mills, respectively. In addition, the production of *A. tequilana* is present in Jalisco and Guanajuato States [23]. Oil palm is produced in the south of Veracruz State, north of Tabasco State and Chiapas State, and the OPEFB are produced after taking all oil-rich fruits for further red oil palm production and in some cases refined oil palm and biodiesel [23], while coffee is produced mainly in Veracruz and Puebla States [12]. The edible tender cladodes (*Opuntia spp.*; *nopal* in Spanish) are mainly commercially produced in the following Mexican States: Morelos, Aguascalientes, and Guanajuato [23]; these are states where sugarcane mills are installed or there are sugarcane mills in their neighboring states.

Gasification Process and Scenarios

The gasification process uses an air current and the solid biomass (Fig. 1). In the case of a humidity larger than 10% water in the solid biomass, a drier must be installed before the gasifier in order to increase the gasification efficiency. The produced gas, or syngas, contains CO, CO_2, H_2O, CH_4, and H_2, besides H_2S derived from sulfur contained in biomass. The hot-produced syngas is used to produce steam in a high recovery steam generator. The H_2S is separated from syngas to avoid corrosion, and

Table 1 Properties of solid biomass used in gasification simulation of processing for bioenergy generation [12, 16, 23, 24]

Component (% mass)	Sugarcane bagasse	OPEFB	Tender cladodes	Agave bagasse	Coffee pulp
C	21.94	41.7	34.72	39.81	40.49
H	2.65	5.5	5.07	5.08	5.32
O	19.31	46.8	55.86	41.61	44.98
N	0.07	1.2	4.32	1.79	2.34
S	0.02	0.49	0.03	0.3	0.33
Moisture	55.0	7.8	50	2.68	2.74
Ash	1.01	4.31	15.32	11.41	6.55
High heating value (MJ/kg)	8.3	15.22	12.73	15.43	16.28

Table 2 Data used in process simulation in scenarios 1 and 2

Parameter	Unit	Value
Conventional sugarcane mill operation		
Operating time of sugarcane mill	h/year	4237
Operating time of bioenergy generation system	h/year	7920
Boiler air excess ratio[1]	%	15
Steam pressure	bar	15.2
Boiler heat losses[1]	%	10
Grid electricity cost [30]	US$/kWh	0.071
Biomass cost	US$/ton	8
Fuel oil cost [31]	US$/GJ	10.8
Boiler feedwater cost [32]	US$/m^3	2.07
Labor hours [2]	h/year	190,665
Labor costs [2*]	US$/h	5
Mexican peso to US$ dollar parity*	MX$/US$	19
Gasification conditions		
Gasification temperature	°C	728
Turbine operation		
Steam turbine outlet pressure	bar	2
Oxygen excess in gas turbine	%	120
Ratio of air compressor pressure		8
Air compressor isentropic efficiency	%	70
Gas turbine isentropic efficiency	%	90
Steam turbine isentropic efficiency	%	85

[1] Assumed data considering typical values used for the type of systems studied in the literature [12, 21–23]

[2] The case of orange is taken as a reference, considering that in the case of bagasse there are three biomass boilers [25]. *At the moment of the study

the latter is sent to a boiler (scenario 1) or a gas turbine (scenario 2) to generate bioenergy. The gasifier produces also a solid residue, biochar, which can also be used as fuel.

In scenario 1, the biomass drier can be present if biomass humidity is higher than 10%. The cold syngas goes to a boiler to generate steam at 15.2 bar and is then sent to mechanical equipment for the sugarcane processing or steam turbines for electricity generation. It is considered that the boiler and turbine are already installed and depreciated in the sugarcane mill, and little modifications must be done in order to use syngas. The steam from the heat recovery system (see Fig. 2) is combined with the boiler steam and sent to the steam turbine to produce electricity.

In scenario 2, a boiler to generate steam from the solid residue is considered, but the steam turbine is replaced for a gas turbine in order to generate electricity from the syngas. Electricity is supplied to the sugarcane mill and any surplus is exported to the grid (Fig. 3). The combustion gases from the gas turbine are at 806 °C, and it is considered a second high recovery steam generator to generate steam. Then, the combustion gases are sent to the biomass drier to dry the high moisture biomass. The solid residue, biochar, might be used in the existent boilers to generate more steam. All steam is sent then to mechanical equipment and existing steam turbine for sugarcane processing and generate electricity as discussed earlier.

The gasifier was simulated using only air as gasifying agent and parameters such as were set in order to get a typical syngas composition according to literature [10].

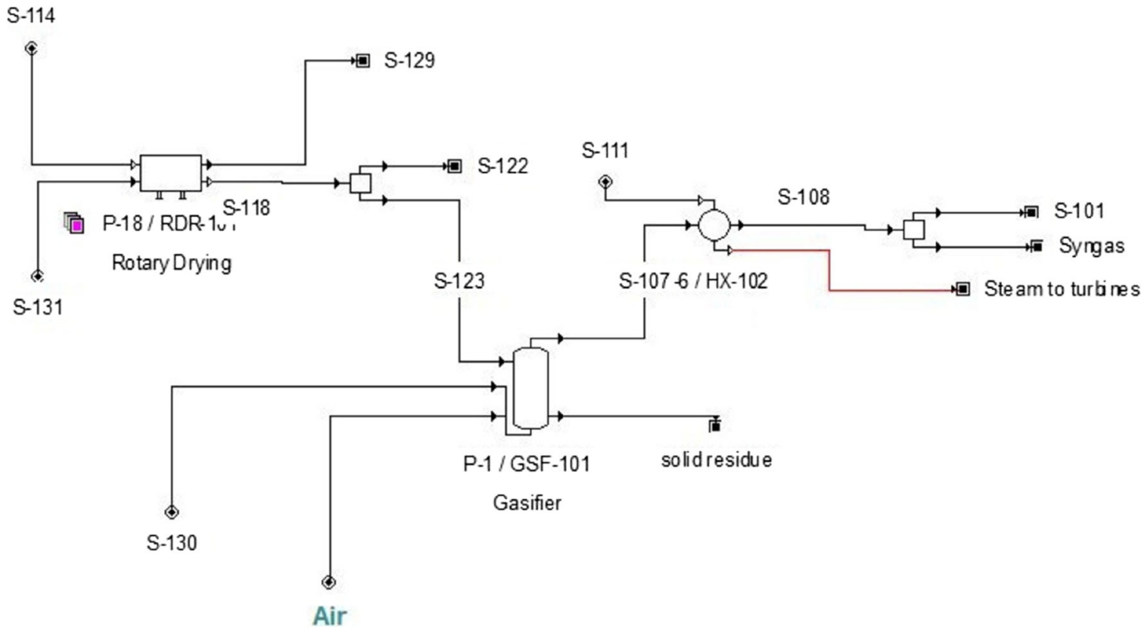

Fig. 1 Gasification process of biomass

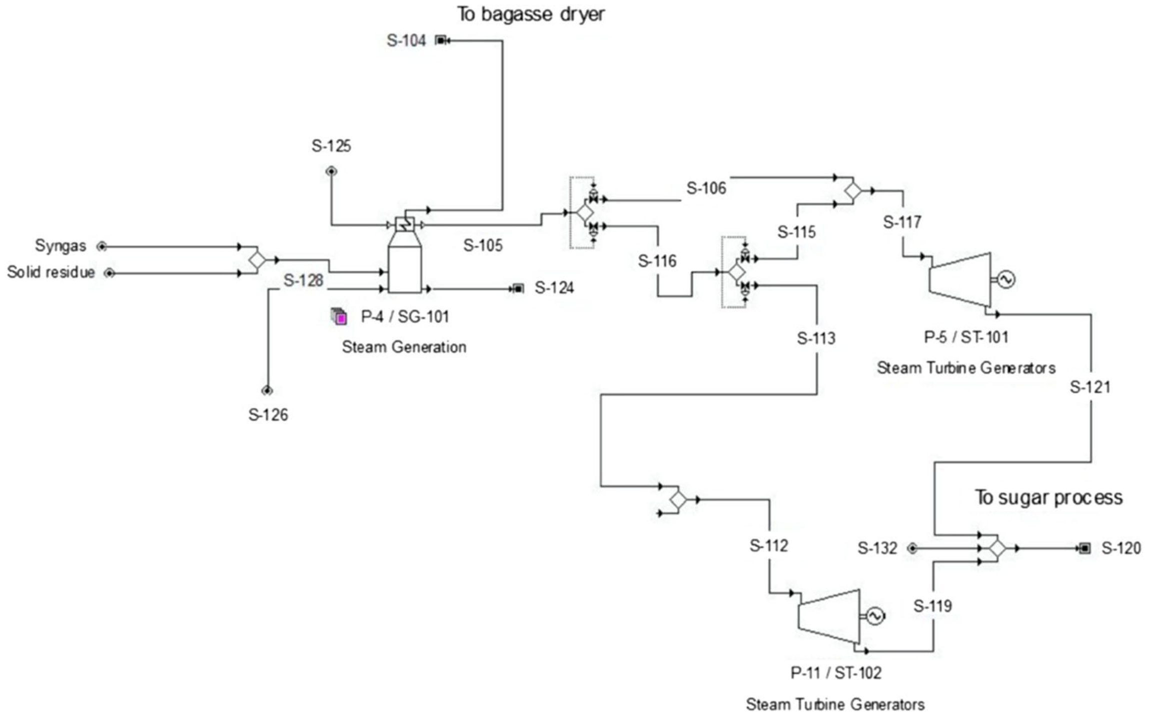

Fig. 2 Bioenergy generation process from biomass syngas using a boiler and a steam turbine (scenario 1)

The parameters set were a 10% heat loss and a conversion of 90% as these parameters allowed obtaining gas composition and gasification efficiencies in the range reported in the literature [14–16]. The equilibrium reaction model available in the simulator SuperPro Designer was used which considers the following chemical reactions [20]:

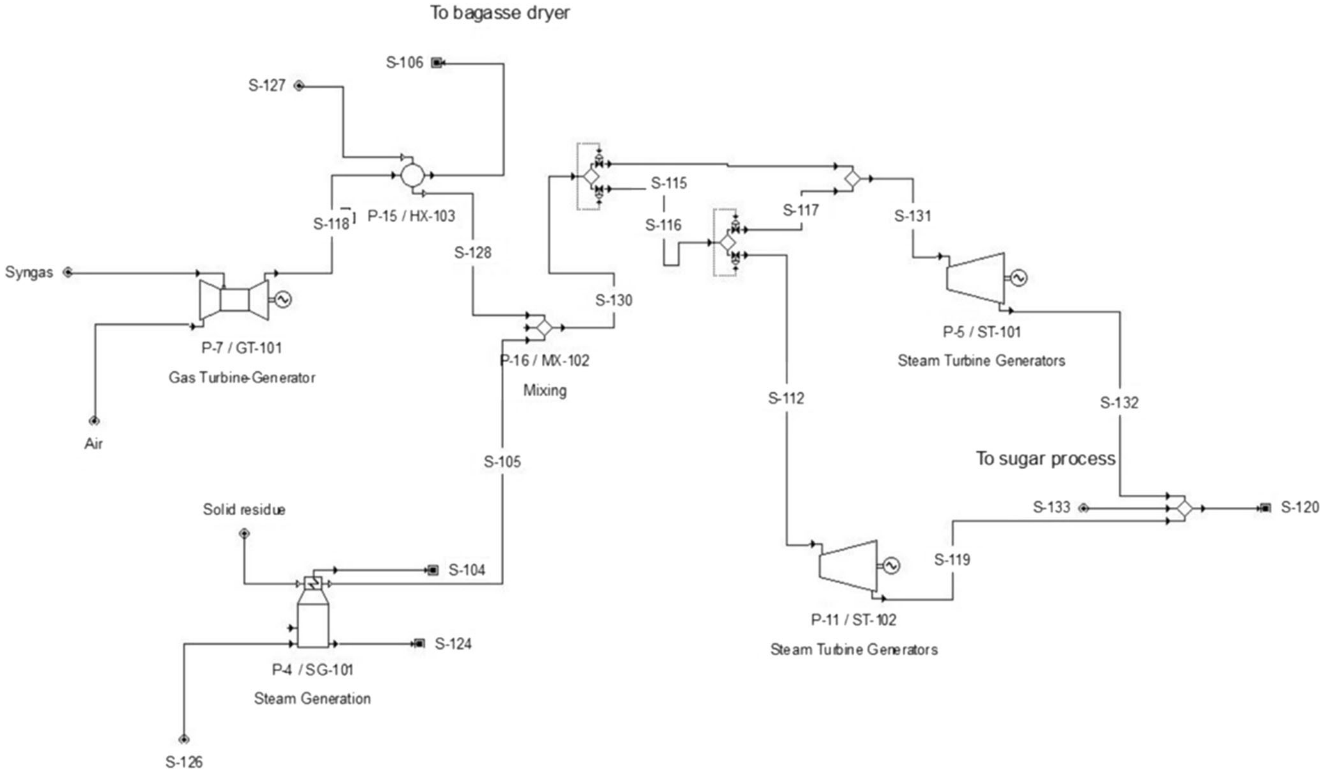

Fig. 3 Bioenergy generation process from biomass syngas using a gas turbine (scenario 2)

Gasification reaction

$$C + H_2O \rightarrow CO + H_2 \quad (1)$$

Boudouard reaction

$$C + CO_2 \rightarrow 2CO \quad (2)$$

Methanation reaction

$$C + 2H_2 \rightarrow CH_4 \quad (3)$$

In addition, the following global gasification reaction is considered by SuperPro Designer model:

$$\begin{aligned} &CH_aO_bN_cS_d + wH_2O + m(O_2 + N_2)— \\ &> n_{CO}CO + n_{H2}H2 + n_{CH4}CH4 + n_{CO2}CO2 \\ &+ n_{H2O}H2O + n_CC + dH2S + (c/2 + rm)N_2 \end{aligned} \quad (4)$$

Where a is the atoms of H per atom of C, b is the atoms of O per atom of C, c is the atoms of N per atom of C, and d is the atoms of S per atom of C. w is the initial moles of H_2O (including biomass moisture) per atom C, m is the initial moles of O_2 per atom C, r is the N_2/O_2 ratio of air, n_{CO2} is the moles of produced CO_2 per atom C, n_{CO} is the moles of produced CO per atom C, n_{H2} is the moles of produced H_2 per atom C, n_{CH4} is the moles of produced CH_4 per atom C, n_{H2O} is the moles of produced H_2O per atom C, and n_C is the moles of unconverted C per atom C. The process simulator SuperPro Designer® considers a very simplified gasification model but enough for the practical nature of this study, and the results were validated with a typical syngas composition and a similar gasification efficiency (ca. 70%) reported in literature [14–16]. The cold gas efficiency of the gasifier (CGE_{HHV}) is calculated by the software using the following equation:

$$CGE_{HHV} = Q_{dg,STP}HHV_{dg}/(F_{db}HHV_{db}) \quad (5)$$

where CGE_{HHV} is the cold gas efficiency on HHV basis for dry biomass (HHV_{db}), F_{db} is the mass flow rate of biomass on dry basis (in kg/s), and $Q_{dg,STP}$ is volumetric dry gas production rate at standard temperature and pressure (STP) (in Nm^3/s).

The software also considers that part of the biomass input is burned in order to provide the necessary energy for gasification, since it considers the equivalence ratio, i.e., the oxygen percentage necessary for the complete biomass combustion (ca. 35%). The amount of air is calculated through the following equation:

$$Fair = F_{biomass}[n(1 + a/4 + d–b/2)M_{O2}/y_{O2}]ER \quad (6)$$

where Fair is the mass flow rate of air (in kg/s), $F_{biomass}$ is the mass flow rate of biomass (in kg/s), M_{O2} is the molar mass of oxygen (in kg/mol), y_{O2} is the mass fraction of oxygen in air (in kg/kg), and ER is the equivalence ratio (i.e., the ratio of actual oxygen amount to the stoichiometric oxygen amount required for complete combustion of biomass).

The parameters used for the simulations are shown in Table 2; the values reported here can be used to replicate or run simulations for other case studies.

The mass and energy balances are obtained from the simulations and used for the calculation of costs. In particular, the net energy generated in the form of steam and electricity can be calculated. Then, the techno-economic analysis was carried out to obtain the bioenergy cost and the payback time. For this, the capital costs (CAPEX) as well as the operation costs (OPEX) were considered. The sum of CAPEX and OPEX give the annual operation total cost (COP, US\$/year) calculated by [33, 36]:

$$COP = E_{imp}{*}p_{el} + W{*}p_w + m{*}p_b + O + CAPEX \quad (7)$$

where E_{imp} is the imported electricity or bought from the grid (kWh/year), p_{el} is the cost of such electricity (US\$/kWh), *W* is the water consumption (ton/year), p_w is the cost of such water (US\$/ton), *m* is the biomass fed to the process (ton/year), p_b is the cost of such biomass, and *O* are other costs such as labor and related to equipment (maintenance is set at annual 2% of initial investment) that are defined in the software. The annual capital cost was fixed at a rate of 8% and 20 life years for the project.

The sugarcane mill has replaced the use of fuel oil by sugarcane bagasse for the cogeneration of steam and electricity; therefore, it is worth to calculate the produced energy unit cost and to consider the savings with respect to the energy produced from the substituted fossil fuel. The total unit cost of energy produced (*CEP*, US\$/GJ) is calculated according to [21, 25]:

$$CEP = {}^{COP}/_{E_p} \quad (8)$$

where E_p is the total produced energy produced (GJ/year), and is the sum of energy in form of steam for processing and produced electricity. In such a manner, the cost of energy unit produced from the fuel oil was obtained and the saving potential determined using biomass for energy generation [21, 25]:

$$S = CEF - CEP \quad (9)$$

where S is the potential savings by energy unit (US \$/GJ), *CEF* is the cost of energy unit produced by the fuel oil (US\$/GJ). Such potential savings are considered as income to determine the payback time. The electricity savings are considered as a credit. The *CEF* value for fuel oil is 14.37 US\$/GJ and estimated from the fuel oil's price (see Table 2) and assuming 85% efficiency, as well as the same values for labor and maintenance as in the case of biomass.

The cost of biomass is 8 US$/ton. It is considered that steam and electricity demand occurred only during sugarcane harvest and processing (*zafra*), but that the energy generation system works along the whole year, which is necessary to increase the economic feasibility of such a gasification system investment. All technical and economical parameters used in the simulation are shown in Table 2.

Results and Discussion

The gasification of several biomasses found in Mexico was simulated in order to get insights about the generation of steam and electricity required during *zafra* time and to prove that such biomasses provide enough energy for the sugar production process and surplus electricity to be exported to the grid outside *zafra* period. Among all tested biomasses, only sugarcane bagasse and tender cladodes have a humidity content of 55 and 50%, respectively; that required a previous drying till 10% humidity. All other biomasses have a humidity minor than 10%.

Syngas Composition

Table 3 shows the syngas composition of all alternative biomasses. The compositions are within the range of values reported in the literature. The CO content (17.49–20.75%) was similar to the one obtained from sugarcane bagasse with 19.07% CO. The other syngas components are higher than when using sugarcane bagasse. Such changes in syngas composition may be explained by the biomass composition, humidity content as well as by the high heating value, and therefore by the air equivalent ratio required in the gasifier. For example, the higher CO and H_2 compositions are related to the higher C and H content of the alternative biomasses in comparison to the sugarcane bagasse composition. The gasification efficiency obtained from the simulations was around 60–70% and the temperature of 728 °C, similar to values reported in the literature [14, 15].

Mass and energy balances for all biomasses in the two scenarios are shown in Table 4. It is observed that the required steam and electricity are produced from the sugarcane bagasse generated in the sugarcane mill in scenario 1 [21, 22]. In scenario 2, it required 3500 tons/day, 22.7% more than in scenario 1. Nevertheless, the energy generated is higher than the required by the mill in scenario 1, and then, it can be exported to the grid. Therefore, the electrical efficiency and feasibility of the system increased if a gas turbine is used in scenario 2. The global efficiency based on the high heating value of the biomass was of 32.8% in scenario 1, while it reached a 46% in scenario 2, which confirms a better efficiency. But it is required more sugarcane bagasse to generate the required steam since more electricity is produced and less energy is left to produce steam. So, the feasibility of scenario 2 depends on sugarcane bagasse availability as well as on the economic results that will be discussed further.

If energy generation wanted to be extended beyond the *zafra* period, it is necessary to look for other available biomasses around or near to the sugarcane mill. We selected four biomass alternatives for gasification and cogeneration in the sugarcane mill: OPEFB, agave bagasse, tender cladodes, and coffee pulp since their availability around sugarcane mills. It is observed that all these biomasses provide the required steam and electricity of the mill along *zafra* period, but the energy efficiency is different among them. Sugarcane bagasse and tender cladodes presented the lower energy efficiencies, and this is attributed to their highest humidity content that enforces the drying of such biomasses before gasification as discussed earlier (Table 4). The elemental composition of biomasses does not change importantly among them, but the humidity and ash content should be taken into consideration since they affect the calorific value of biomasses and therefore the thermal instead of electrical energy that can be recovered through thermal processes as gasification. The highest energy efficiencies were obtained with OPEFB, agave bagasse, and coffee

Table 3 Syngas composition and its calorific value produced from several biomasses for cogeneration

Component	Sugarcane bagasse from literature [15]	Sugarcane bagasse (this study)	OPEFB	Tender cladodes	Agave bagasse	Coffee pulp
CO_2 (%)	10–20	12.37	17.45	14.96	17.61	17.73
CO (%)	10–20	19.07	20.42	17.49	20.61	20.75
H_2 (%)	9–20	18.45	24.28	20.79	24.5	24.66
CH_4 (%)	1–8	0.56	5.43	4.65	5.48	5.52
N_2 (%)	40–55	49.53	32.28	42.11	31.39	31.24
Low heating value (MJ/ m^3)*	4–6.5	4.54	7.08	6.04	7.04	7.01

*At normal pressure and temperature conditions

Table 4 Mass and energy balance for the gasification of several biomasses employing a steam turbine (scenario 1) or gas turbine (scenario 2) for steam and electricity cogeneration in a sugarcane mill

Parameter	Scenario 1	Scenario 2	Scenario 1	Scenario 2	Scenario 1
Required biomass, (ton/day)	2852.40	3500.00	1020.00	1850.00	4130.00
Produced dried syngas, (Nm3/h)	138,774.00	170,278.50	97,507.85	142,687.17	118,024.32
Steam to process, (ton/h)	212.50	212.70	212.85	212.76	212.54
Required steam in process, (ton/h)	212.35	212.35	212.35	212.35	212.35
Energy in steam, (kWh/year)	549,831,253.00	549,831,253.00	549,831,253.00	549,831,253.00	549,831,253.00
Electric power generated in steam turbine, (kW)	9616.11	8607.50	10,972.82	21,874.14	9485.66
Electric power generated in gas turbine, (kW)	0.00	66,875.90	0.00	88,136.75	0.00
Consumed power in *zafra* period, (kW)	4697.00	4697.00	4697.00	4697.00	4697.00
Power deliver to equipments in *zafra* period (kW)	10,973.00	10,973.00	18,753.26	19,154.72	10,972.82
Generated electricity in *zafra* period, (kWh/year)	40,743,458.00	319,823,081.00	46,491,838.34	466,116,140.93	40,190,741.42
Consumed electricity in *zafra* period, (kWh/year)	19,901,189.00	19,901,189.00	19,901,189.00	19,901,189.00	19,901,189.00
Electricity exported to the grid en *zafra* period, (kWh/year)	20,842,269.00	299,921,892.00	26,590,649.34	446,214,951.93	20,289,552.42
Electricity exported to the grid out of *zafra* period, (kWh/year)	75,829,029.00	314,319,300.00	109,481,152.64	475,716,941.63	20,289,552.42
Total exported electricity, (kWh/year)	96,671,298.00	367,937,326.00	136,071,801.98	921,931,893.56	95,245,084.50
Initial energy in biomass, (kWh/year)	2,170,220,782.00	2,662,916,666.67	1,423,070,000.00	2,581,058,333.33	2,117,605,875.00
Total generated energy (steam + electricity), (kWh/year)	712,895,579.00	1,225,750,031.00	785,261,806.60	1,572,822,884.20	711,469,364.84
Energy efficiency (%)	32.84	56.50	55.18	60.94	33.60

Parameter	Scenario 2	Scenario 1	Scenario 2	Scenario 1	Scenario 2
Required biomass, (ton/day)	4750.00	1033.00	1825.00	1043.00	1720.00
Produced dried syngas, (Nm3/h)	135,742.30	91,858.12	151,577.22	93,829.63	154,102.65
Steam to process, (ton/h)	212.70	212.63	212.36	212.65	212.59
Required steam in process, (ton/h)	212.35	212.35	212.35	212.35	212.35
Energy in steam, (kWh/year)	549,831,253.00	549,831,253.00	549,831,253.00	549,831,253.00	549,831,253.00
Electric power generated in steam turbine, (kW)	8763.60	10,972.82	21,818.00	10,972.82	18,740.81
Electric power generated in gas turbine, (kW)	54,262.33	0.00	89,414.41	0.00	89,372.57
Consumed power in *zafra* period, (kW)	4697.00	4697.00	4697.00	4697.00	4697.00
Power deliver to equipments in *zafra* period (kW)	10,972.82	10,347.72	19,029.47	12,160.81	21,454.13
Generated electricity in *zafra* period, (kWh/year)	267,040,865.41	46,491,838.34	471,291,721.17	46,491,838.34	458,076,391.06
Consumed electricity in *zafra* period, (kWh/year)	19,901,189.00	19,901,189.00	19,901,189.00	19,901,189.00	19,901,189.00
Electricity exported to the grid en *zafra* period, (kWh/year)	247,139,676.41	26,590,649.34	451,390,532.17	26,590,649.34	438,175,202.06
Electricity exported to the grid out of *zafra* period, (kWh/year)	269,081,232.22	78,523,548.82	479,754,504.04	85,201,159.29	477,197,139.33
Total exported electricity, (kWh/year)	516,220,908.63	105,114,198.16	931,145,036.21	111,791,808.63	915,372,341.39
Initial energy in biomass, (kWh/year)	2,435,503,125.00	1,461,092,416.67	2,581,310,416.67	1,556,503,666.67	2,566,813,333.33
Total generated energy (steam + electricity), (kWh/year)	1,128,469,145.80	718,689,929.80	1,581,505,342.60	733,049,602.60	1,576,005,932.20
Energy efficiency (%)	46.33	49.19	61.27	47.10	61.40

pulp, but it is still higher than that obtained for sugarcane bagasse and tender cladodes in scenarios 1 and 2.

Economic Analysis

Concerning economic analysis, the energy production cost and the investment and payback times are shown in Fig. 4. As it is observed in the case of investment (Fig. 4a), it is higher in scenario 1 for tender cladodes, followed by sugarcane bagasse OPEFB, agave bagasse, and coffee pulp. This can be attributed to the use of a drier to get 10% humidity for such biomasses, while the latter three biomasses have a humidity lower than 10% and the drying process was not needed. Here, it is assumed that such biomasses were dried at production sites and transported to the sugarcane mill. Concerning scenario 2, the investment is higher than scenario 1 in all cases due to the additional cost of the gas turbine as well as for a bigger processing capacity. Nevertheless, the cost of produced energy (CEP; Fig. 4b) when no biomass cost is assumed, diminishes progressively in the following order: tender cladodes > sugarcane bagasse > agave bagasse > coffee pulp > OPEFB, both for scenarios 1 and 2. However, the CEP is 30% lower in scenario 2 than in scenario 1 for all biomasses since there is more generation of electricity.

When a biomass cost of 8 US$/ton is considered, the behavior among all biomasses is the same but at a slightly higher cost for both scenarios. The scenario 2 presented

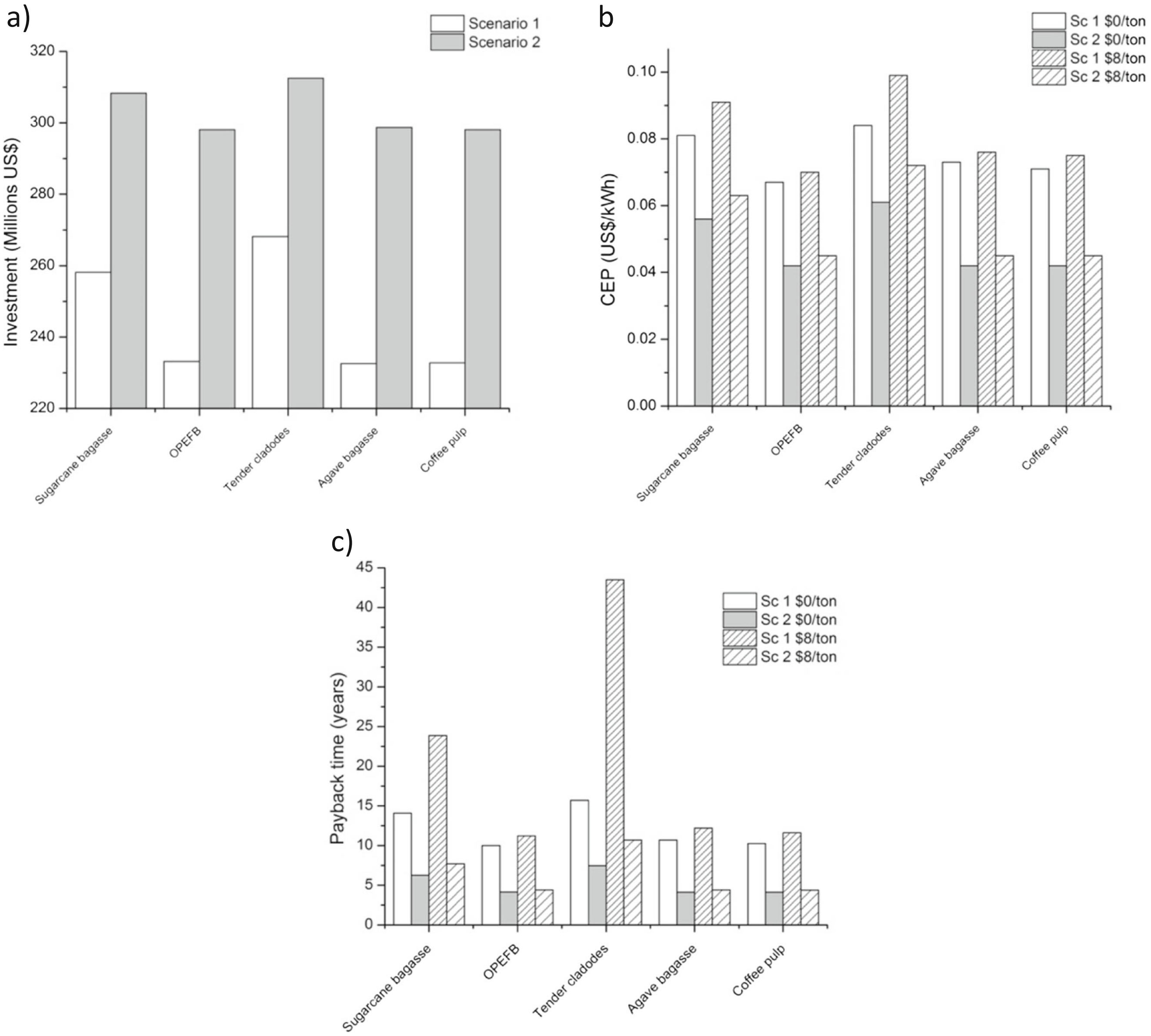

Fig. 4 Economic results for the gasification of all biomasses in scenario (Sc) 1 and 2. **a** Investment. **b** The cost of total produced bioenergy unit (CEP). **c** Payback time. Oil palm empty fruit bunch (OPEFB)

lower CEP values when compared to scenario 1 as discussed earlier. So, it can be observed that the CEP value of sugarcane bagasse in scenario 1 (0.091 US$/KWh) is higher than the cost of the electricity from the grid (0.077 US$/kWh), while in scenario 2 is lower (0.063 US$/kWh) and can be then exported to the grid at a competitive price. In both scenarios, the major contribution to the annual costs come for the necessary investment in ca. 83%. For example, the buying cost (not installed) of the gasifier is 79.6 million US$, the gas turbine is 18.1 million US$ and the driers 11 million US$ as estimated by the software. For all other biomasses, the *CEP* value is less than 0.077 US $/kWh in both scenarios 1 and 2, except for tender cladodes in scenario 1, where the electricity production was not enough to sufficiently lower its cost. The OPEFB is the more attractive biomass for energy generation in both scenarios, and this was attributed to the lower biomass required per unit of energy generated and associated with a lower humidity content as well as a higher syngas heating value of 7 MJ/m^3 at normal conditions.

Considering the payback time, this is of 7.7 years for sugarcane bagasse in scenario 2 at a biomass cost of 8 US $/ton, while the payback time of 24 years for scenario 1 is prohibitive (Fig. 4c). So, the use of a gas turbine is the best system for energy generation using sugarcane bagasse gasification. All other biomasses showed a lower payback time for both scenarios than for the sugarcane bagasse, except for tender cladodes. With respect to scenario 2, the payback time diminishes to 4.4 years for OPEFB, agave bagasse, and coffee pulp.

Additionally, the economic analysis was performed considering a sugarcane bagasse cost of 0 US$/ton to evaluate if the payback time diminishes. It is observed that the CEP (Fig. 4b) and the payback time (Fig. 4c) showed that scenario 1 is not attractive, while scenario 2 allows a lower payback time of 6.3 years and reducing the CEP to 0.056 US$/kWh. Nevertheless, such cost is even higher than the cost with the current combustion system of the sugarcane mill (CEP = 0.0198 US$/kWh; [23, 25]), mainly due to the major investment for scenario 2. However, this must be compared to the cost in a combustion system where a flue gas cleaning system would be required to comply with stricter environmental regulations regarding particulate matter and carbon black emissions. For all other biomasses with a cost of 0 US$/ton, the CEP diminishes to 0.42 US$/ton and a payback time of 4.1 years, except for tender cladodes.

Conclusions

In this work, the techno-economic aspects of the use of sugarcane bagasse have been investigated by gasification for energy generation as well as the use of five types of biomass in two scenarios. The results showed that for all solid biofuels in scenario 1, where the syngas is burned directly in boilers to generate steam and then expanded in turbines, is not attractive from the cost point of view of cost of energy produced or payback time. Scenario 2, based on biomass gasification technology and using synthesis gas in a gas turbine, offers a cost of bioenergy production that is competitive considering the price of grid electricity, but requires a much higher investment since it is a more complex system than the one based on direct biomass combustion. That means a recovery time greater than the direct combustion system but acceptable for the useful lifetime of the equipment. Therefore, if the additional amount of bagasse or local biomass can be provided to the gasifier, the system of scenario 2 is recommended, considering a gas turbine that makes the most of the synthesis gas for electricity generation. This facility is required to operate both within and outside of the harvest and processing season (*zafra* period) for a better use of investment and bagasse, since efficiency is greater in this scenario. The added value is that it can handle a greater amount of bagasse or other biomass, export a greater amount of electricity at a low cost, and reduce particle emissions.

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Data Availability The datasets generated and analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics Approval and Consent to Participate This manuscript does not contain any studies with human participants or animals performed by any of the authors.

Consent for Publication This manuscript does not contain any other authors. The author consent for publication. No need consent from any other authors.

Competing Interests The authors have no conflicts of interest to declare that are relevant to the content of this article.

Abbreviations *SB,* Solid biofuel; *OPEFB,* Oil palm empty fruit bunches; *CAPEX,* Capital costs; *OPEX,* Operation costs; *COP,* Annual operation total cost; *CEP,* Cost of total produced bioenergy unit

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