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# COMPARISON BETWEEN TWO ALTERNATIVES FOR THE ENERGY USE OF VINASSE: CONCENTRATION-INCINERATION VS BIODIGESTION

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***Abstract.*** *The vinasse, effluent generated in the distillation step of the ethanol production process, has polluting characteristics and is generated in large amounts, making its disposition problematic and costly. This work addresses the vinasse problem in the ethanol production from sugarcane, through a comparison between two alternatives to treat it with energy recovery: i) concentration in a multiple-effect evaporator system and subsequent incineration; and ii) biodigestion. The comparison is carried out through mass and energy balances for the proposed routes evaluating two configurations of the cogeneration system; Configuration 1, using back-pressure steam turbines (BPST); and Configuration 2, using condensing-extraction steam turbines (CEST). Results indicated that for cases using CEST (where the electricity surplus is maximised), the electricity surplus resulted in the same range: 86.82 kWh/t of cane for the concentration-incineration route, and 84.81 kWh/t cane for the biodigestion route. Regarding cases with BPST, the concentration-incineration case presented a potential of 70.24 kWh/t cane of electricity surplus, which is 33.4% higher than the electricity surplus in the biodigestion case, because of the additional steam consumption in the vinasse concentration process; however, the bagasse surplus in this case resulted in 27.37 kg/t cane, which is 48.4% lower in comparison to the biodigestion case. Regarding the economic assessment, the concentration with incineration of vinasse presented better results of total annualised costs for CEST; while the biodigestion route was a better option for BPST.*

*Keywords: biodigestion, concentration, incineration, vinasse*

## 1. INTRODUCTION

The sugar and ethanol industry from sugarcane has an important role in the Brazilian agribusiness. The ethanol production, particularly, had a boost with the National Ethanol Program, or Proálcool, created in 1975 by the Brazilian government, as a solution to the oil crisis in 1973. This program raised the Brazilian energy security. Not only is the ethanol a renewable fuel, but also, the energy contained in the Brazilian ethanol is 370% higher than the energy spent in its production (Andrade *et al*., 2009). Nowadays, the Brazilian government, through the Ministry of Mines and Energy, is presenting the RenovaBio Program which seeks to expand the biofuel production (J. M. Coelho, 2017), being the ethanol among the biofuels contemplated. Thus, with an increasing ethanol production, the vinasse, the liquid residue of this production process, produced as the bottom product of the distillation column in the distillation step, will increase as well. This residue represents a current problem for the industry because of its polluting characteristics and large volume generated. The vinasse is a dark brown liquid of acidic nature, and leaves the distillation column at approximately 107°C. In distillation integrated units, the vinasse pre-heats the fed wine and its temperature is reduced until approximately 77°C (Pina et al., 2017). Owing to its high organic matter content, a putrefaction process starts as soon as the vinasse is discharged, which represents social problems for the communities located close to the plants, due to the fetid odours generated (Freire & Cortez, 2000). The vinasse production rate varies with the ethanol content in the wine, and, according to Freire and Cortez (2000), it ranges from 10 to 15 litres of vinasse per litre of ethanol produced.

Currently, this effluent is being disposed through fertirrigation, which consists in the aspersion of the vinasse on the crops to take advantage of its solid content, which is rich in potassium, phosphorous, nitrogen, sodium and calcium, and

its high water content to fertilise and irrigate at the same time (Freire & Cortez, 2000). However, this form of disposition, in the state of Sao Paulo, is regulated by the government, taking into account the crop needs, level of potassium in the soil, potassium content in the vinasse, and type of soil, among others (CETESB, 2015; Neto & Shintaku, 2009a). Since vinasse has a significant mineral content, an excessive dose, or the application in an inappropriate soil can lead to environmental problems such as leaching and pollution of groundwater, as well as soil salination (Penatti & Donzelli, 2000).

Among the alternatives for the use of vinasse, the biodigestion and incineration in boilers are of special interest because of their potential to generate electric energy when coupled with a cogeneration system, which is usually used in sugarcane-processing plants. This way, this work seeks the comparison of these two technologies for the energy use of vinasse, by way of energy and economic analyses.

## 1.1 Incineration of vinasse

The direct combustion, or incineration, is a technology that allows an almost complete disposition, and a definitive elimination of the polluting potential of vinasse. Besides, it permits the recovery of mineral-containing ashes, which can be used to fertilise the sugarcane crops (Freire & Cortez, 2000). As the water content of vinasse, as it is produced, is rather high (an average of 93%, wt % (Christofoletti et al., 2013)), its incineration is impossible, as it is produced; for this reason, a concentration step is necessary prior to the incineration, to increase the solid content up to a concentration that can enable the incineration of this effluent. Some studies have reported that a concentrated vinasse with a solid content between 60 and 70% is enough to incinerate it. In this work, a multiple-effect evaporator system was considered since it is the most spread technology, and it is widely used in the ethanol and sugar industry. In a multiple-effect evaporator system, several evaporators are assembled in series, so that the first effect uses exhaust steam as heat source, while the subsequent effects use the vapour generated in the separation process, called *vegetal vapour*, of the previous effect.

## 1.2 Biodigestion

The anaerobic biodigestion is a complex biochemical process in which a large number of facultative and obligate anaerobes absorb and break the organic matter, degrading it in the absence of oxygen (Cheremisinoff, 1996). The biodigestion of vinasse can be considered as an alternative treatment that allows the reduction of its polluting potential, and the valorisation of this effluent through the obtainment of energy using the biogas produced (Neto & Shintaku, 2009; Salomon et al., 2011). The biodigestion of vinasse can be considered because of its high Chemical and Biological Oxygen Demand (COD and BOD), and low solid content. Still, the biodigestion does not completely eliminate the polluting potential, nor does it resolve the problem of the large volume of vinasse. Nevertheless, the biodigested vinasse keeps its nutrients which can be used as fertilisers. In addition, the biodigestion stabilises the organic matter, reducing its BOD, as well as increasing the pH; thus allowing a safer disposition in the crops (Cortez et al., 2010; Salomon et al., 2011).

## 2. METHODOLOGY

The assessment of the energy potential was carried out by analysing and comparing three cases. A Base Case, or Case i, which considers the conventional ethanol, sugar and electricity production process; Case ii, which considers the vinasse concentration in a multiple-effect evaporation system, with the subsequent incineration of the concentrated vinasse in the boiler of the cogeneration system; and Case iii, which considers the biodigestion of vinasse, with the subsequent burning of the produced biogas in the boiler of the cogeneration system. The evaluated cases are described in the following sections.

## 2.1 Case i: Conventional ethanol, sugar and electricity production process

Case i was considered as a conventional ethanol, sugar and electricity production process. A plant processing 500 tonnes of cane per hour, and consuming steam at 2.5 bar was simulated utilising the software Aspen Plus™. The guidelines for the simulation were taken from Ensinas (2008) and Palacios-Bereche (2011); and data from the literature were gathered. The cogeneration system was simulated utilising the software EES®. Figure 1 presents a simplified flowsheet representing the sub-systems of the conventional process.
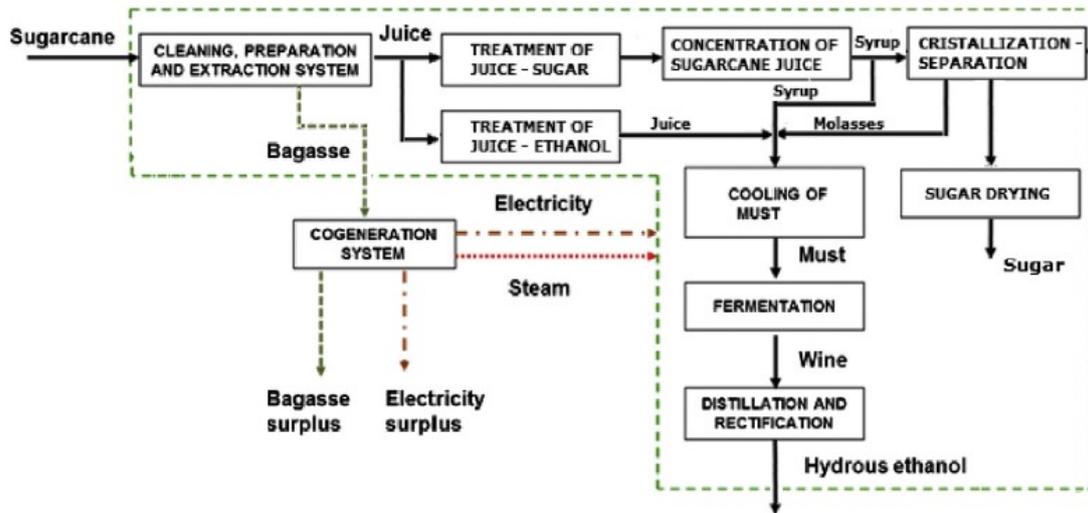
Figure 1. Flowsheet of Case i: Conventional ethanol, sugar and electricity production process. Modified from Pina *et al*. (2017).

## 2.2 Case ii: Vinasse concentration and incineration

Case ii was considered as a Case i coupled to a vinasse concentration system, which sends the concentrated vinasse to the boiler of the cogeneration system; as can be observed in Figure 2. The vinasse concentration system was assumed to be a seven-effect evaporation system, since some manufacturers commercialise this kind of evaporators (CITROTEC, 2012). A simplified scheme of the system considered in this study is presented in Figure 3. Mass and energy balances were carried out for each effect utilising the software EES®.
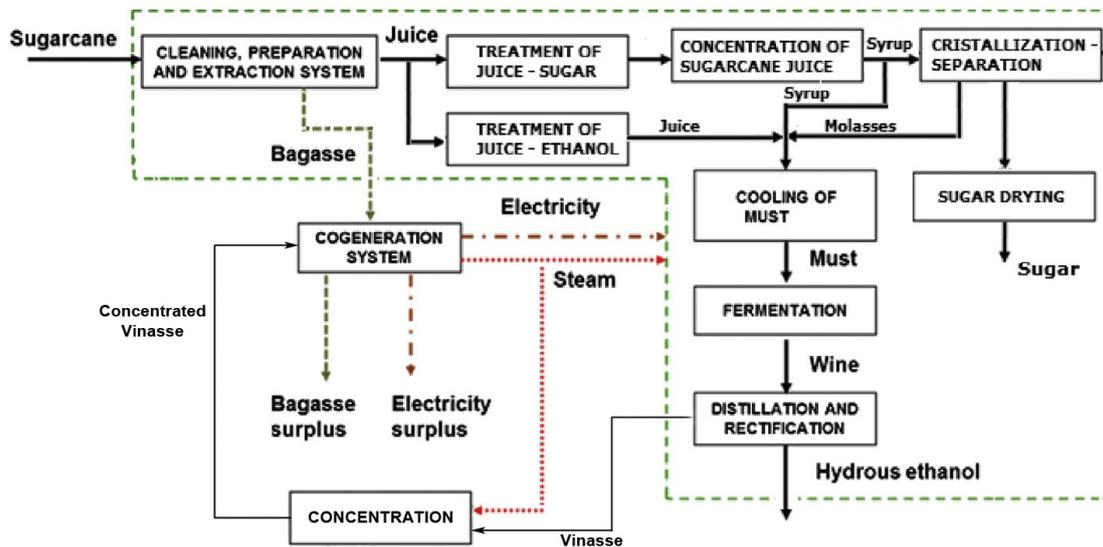


Figure 2. Flowsheet of Case ii: Case i + Vinasse concentration system. Modified from Pina *et al*. (2017).
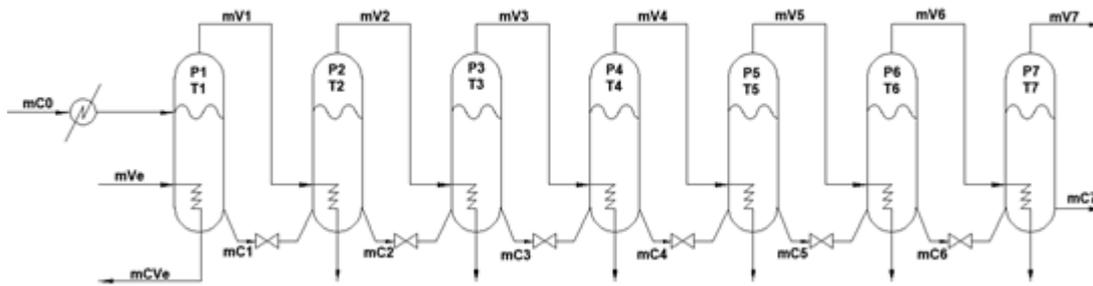
Figure 3. Diagram of a seven-effect evaporation system for vinasse.

In Figure 3, $mCi$ represents the mass flow of vinasse which is being concentrated in each effect, $mVi$ the vegetal vapour separated in each effect, and $mVe$ and $mCVe$ the mass flows of the exhaust steam and condensate, respectively, whose enthalpy difference is used in the first effect as heat source. In Figure 2, the vinasse concentration system receives saturated steam ($mVe$) from the cogeneration system and sends the concentrated vinasse ($mC7$) to the boiler of the cogeneration system.

The enthalpy of vinasse was calculated following the equations presented by Larsson & Tengberg (2014):

$$h_{vinasse} = Cp_{vinasse} \times T \tag{1}$$

$$Cp_{vinasse} = \left(\frac{100 - Brix}{100}\right) \times Cp_{H_2O} + \left(\frac{Brix}{100}\right) \times 1.270 \tag{2}$$

Where $Cp$ is the specific heat in kJ/kg-°C and $T$ is in °C. The pressures used in each effect of the vinasse concentration system are presented in Table 1:

Table 1. Pressure of the effects of the vinasse concentration system (Fukushima, 2016)

| Effect | P (bar) |
|--------|---------|
| 1 | 2.139 |
| 2 | 1.788 |
| 3 | 1.449 |
| 4 | 1.12 |
| 5 | 0.802 |
| 6 | 0.496 |
| 7 | 0.2 |

## 2.3 Case iii: Biodigestion of vinasse

Case iii considered the Case i coupled to a biodigestion system consisting of an Anaerobic Structured Bed Reactor (ASTBR) operating at thermophilic temperature. According to Fuess *et al.* (2017), this type of reactor presents the advantage of being less sensitive to environmental variations. Figure 4 shows a scheme of said reactor. The biodigestion system sends the biogas produced to the boiler of the cogeneration system; as can be observed in Figure 5. Mass and energy balances were carried out utilising the software EES®.
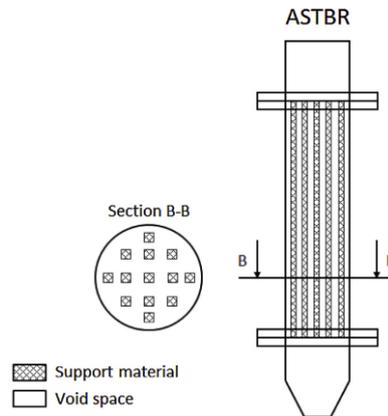
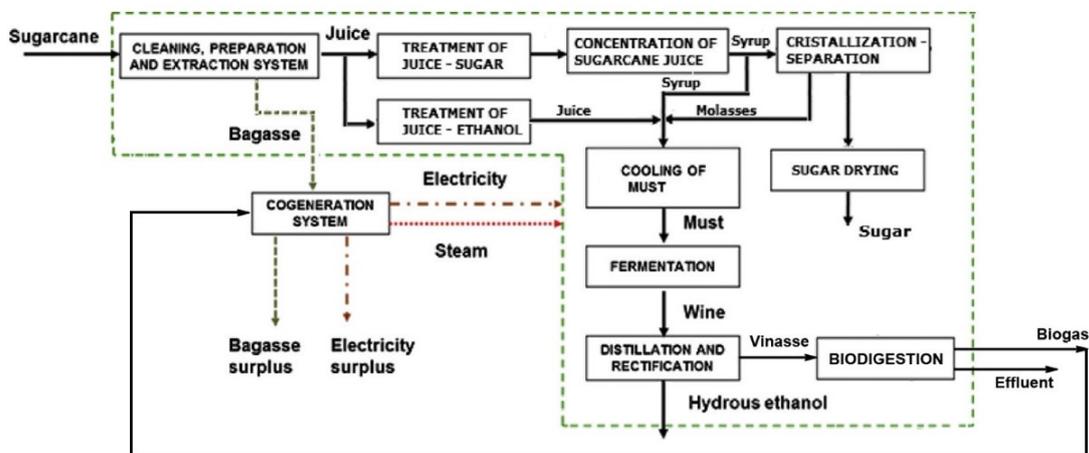Figure 4. Diagram of an ASTBR. (Fuess et al., 2017)



Figure 5. Flowsheet of Case iii: Case i + Vinasse biodigestion. Modified from Pina *et al*. (2017).

In Case iii, the biogas production *(BP)* was calculated following the equation presented by Lamo (1991) cited in Flores-Zavala (2016):

$$BP \cdot \left( \frac{Nm^3}{s} \right) = VV \cdot COD \cdot E \cdot F \tag{3}$$

where:

COD:        Chemical Oxygen Demand, kg COD/$m^3$
E:          COD removal efficiency, %
F:          Biogas factor conversion, $Nm^3$/kg COD
VV:         Vinasse flow rate, $m^3$/s

## 2.4 Cogeneration System

Cogeneration systems generate electricity and thermal energy, as well as mechanical energy in some cases; in one integrated system (Flin, 2009). A steam cycle is usually used as the cogeneration system in sugarcane-processing plants, using sugarcane bagasse as fuel in the boiler. This cogeneration system supplies the requirements of steam, electricity and/or mechanical work in the plant. Two configurations were adopted in this work: Configuration 1 considering back-pressure steam turbines (BPST), and Configuration 2 considering condensing-extraction steam turbines (CEST). Figure 6 presents the schemes of these configurations.
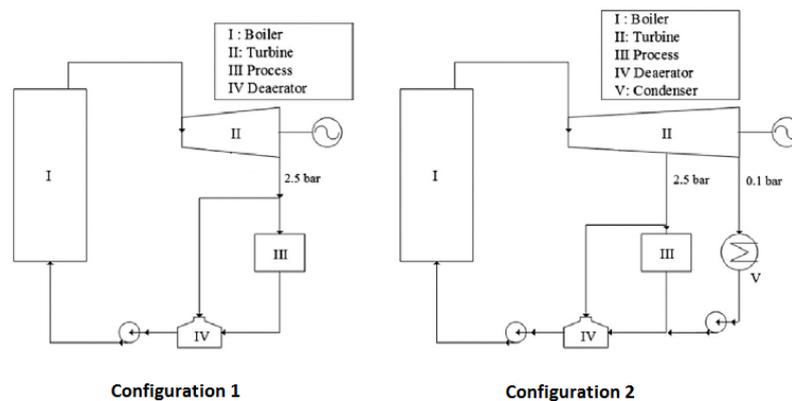
Figure 6. Configurations of the cogeneration system adopted. Modified from Pina *et al.*, (2017)

The calculations regarding cogeneration systems for Case ii and Case iii were performed using the EES software to resolve the mass and energy balances. Furthermore, the cogeneration system was assumed to produce steam at 520°C and 65 bar (Sosa-Arnao, 2018).

## 2.5 Economic assessment

Data from the literature were gathered to perform the economic assessment of the considered cases. The capital costs were annualised using a fractional interest rate per year (*i*) of 10%, and considering 15 years (*n*). For Cases ii and iii, the sale of the additional electricity surplus obtained with the implementation of the technologies proposed, was considered as revenue. Furthermore, the selling of the boiler ashes was considered as an additional revenue in Case ii. According to Cacuro & Waldman (2015), different metal oxides are formed during the incineration of biomass, such as $K_2O$, $MgO$, $P_2O_5$, and $Cao$, among others; which can be used as fertilisers. Thus, the content of triple superphosphate (46% $P_2O_5$ equivalent) and potassium chloride (60% $K_2O$ equivalent) in the vinasse, as it is produced (Simões *et al.*, 2004), is assumed to remain in the boiler ashes, and the selling price of the ashes was considered equal to the selling price of triple superphosphate and potassium chloride fertilisers.

Regarding Case ii, the condensates from the vinasse concentration system were assumed to be re-used in the process (Mello, 2012). The amount of water recovery from vinasse (condensates in this case) was 415.2 kg/t cane, it allows reducing the effective water demand of the mill (1,132 kg/t cane according to Pina *et al.* 2017) to 716.8 kg/t of cane; in that way, no cost was considered for the disposition of the condensates.

In Case iii, the fertirrigation was considered as a mean of final disposition for the biodigested vinasse in the plantation, as this practice is commonly implemented in Brazilian sugarcane-processing plants. A cost of 7.97 R$/m³ of vinasse transported and applied was assumed, as reported in Barbosa (2018). No capital costs were considered, as it was assumed that the plant already has a vinasse fertirrigation system. The different capital and operating costs considered are presented in Table 2.

Table 2. Capital and operating costs for the economic assessment.

| Description | Capital cost | Operating cost |
|---|---|---|
| **Case ii: Concentration + Incineration** | | |
| Concentrator, R$/(t/h) | 80,000 [1] | - |
| Caustic soda for cleaning, R$/t | - | 800 [1] |
| Caustic soda applied, t/week | - | 11.2 [1] |
| Labour force, R$/(labourer/year) | - | 35,000 [1] |
| Number of labourers | - | 4 [1] |
| Supplies and administration, R$/year | - | 83,631.7 [1] |
| Hydroblasting (cleaning), R$/year | - | 418,158.5 [1] |
| Other labour force and materials, R$/year | - | 487,851.5 [1] |
| **Case iii: Biodigestion** | | |
| Investment cost of an AD plant (ASTBR); USD($m^3_{vinasse}$·day⁻¹)⁻¹ | 708.72 [2] | - |
| Operating cost of the AD plant | - | 2.5% of investment cost per year [2] |
| Biogas transportation, USD($Nm^3_{biogas}$·day⁻¹)⁻¹ | 0.096 [2] | 2.5% of investment cost per year [2] |

| | | |
|---|---|---|
| H$_2$S removal device, € | 19,000 [2] | 0.0026 €/Nm$^3_{biogas}$ [2] |
| Fertirrigation cost, R\$/m$^3$ | - | 7.97 [3] |

AD: Anaerobic Digestion; [1] scaled from Poveda (2014); [2] Fuess & Zaiat (2018); [3] Barbosa (2018);

The cost of the exhaust steam (saturated vapour at 2.5 bar) utilised in the concentration of vinasse, was calculated following the guidelines presented in Smith (2005), which are described next:

First, the bagasse cost ($C_{bagasse}$) per energy unit (R\$/kJ) was calculated using (4).

$$C_{bagasse} = \frac{Bagasse\ cost[R\$/t]}{LHV_{bagasse}} \tag{4}$$

Then, the cost ($C_{HPsteam}$) of the steam produced in the boiler (HP steam) is calculated applying (5), where $h_{HPsteam}$ and $h_{boiler\ feed\ water}$ are the enthalpies of the steam generated in the boiler and the feed water, respectively; $\eta_{boiler}$ is the boiler efficiency; and $l_o$ are losses from the steam distribution system (distribution losses).

$$C_{HPsteam} = C_{bagasse} \times \left(h_{HPsteam} - h_{boilerfeedwater}\right) \times \left(\frac{1}{\eta_{boiler} - l_o}\right) \tag{5}$$

The cost of the electricity per kg of steam that pass through the turbine ($C_{EE}$) is then calculated from the work of the turbine ($w_{turbine}$) and the electricity price ($P_{electricity}$) (6):

$$C_{EE} = w_{turbine} \times P_{electricity} \tag{6}$$

Finally, the cost of the exhaust steam ($C_{exhaust\ steam}$) is calculated by subtracting the cost of the electricity produced in the turbine ($C_{EE}$) from the cost of the HP steam ($C_{HP\ steam}$); as represented in (7).

$$C_{exhauststeam} = C_{HPsteam} - C_{EE} \tag{7}$$

The capital costs were annualised using (8):

$$Annualised\ capital\ cost = Capital\ cost \times \frac{\left[i(1+i)^n\right]}{(1+i)^n - 1} \tag{8}$$

An additional cost for the scaling of the cogeneration system was calculated considering the increasing in generated steam and electricity surplus, for the scaling of the boiler and turbine, applying (9) (Bejan *et al*., 1996):

$$C_{eq.desired} = C_{eq.data} \times \left(\frac{Cap_{desired}}{Cap_{data}}\right)^{\alpha} \tag{9}$$

where $C_{eq.desired}$ is the cost of the equipment at the desired capacity ($Cap_{desired}$) calculated from the cost of the same equipment ($C_{eq.data}$) at a given capacity ($Cap_{data}$), and $\alpha$ is the scaling factor.

## 2.6 Main parameters for simulation and input for economic assessment

Table 3 presents the main parameters used in the simulation of the three evaluated cases.

Table 3. Main parameters for simulation and input for economic assessment.

| Parameter | Value |
|---|---|
| ***Simulation*** | |
| *Vinasse concentration* | |
| Vinasse initial brix, % | 4.39 [1] |
| Vinasse final brix, % | 65 [4] |
| *Vinasse biodigestion* | |
| Vinasse COD, kg/m$^3$ | 23.8 [5] |

| | |
|---|---|
| Efficiency of COD removal, % | 80 [6] |
| Biogas conversion factor, $Nm^3_{biogas}$/kg COD | 0.5 [6] |
| $\rho_{biogas}$, kg/$Nm^3$ | 0.784 [7] |
| *Biogas composition* | |
| $CH_4$, % mol (dry basis) | 60 [8] |
| $CO_2$, % mol (dry basis) | 38.1 [8] |
| $H_2S$, % mol (dry basis) | 1.9 [8] |
| $H_2O$, % mol | 5.5 [8] |
| *Cogeneration* | |
| Sugarcane processed, t cane/h | 500 [9] |
| Steam consumption in conventional process (*Case i*), kg/t cane | 437.6 [1] |
| Total produced bagasse, kg/t cane | 272.0 [1] |
| Bagasse for filters, kg/t cane | 5 [1] |
| Bagasse for self-consumption, % of total bagasse | 5 [10] |
| Bagasse LHV (50% of humidity), MJ/kg | 7.64 [2] |
| Vinasse $HHV_{dry}$, MJ/kg | 13.53 [11] |
| Biogas LHV, MJ/kg | 17.14 [2] |
| $\eta_{boiler}$, % | 85 [12] |
| $\eta_{turbine}$, % | 80 [12] |
| $\eta_{pump}$, % | 80 [12] |
| Electricity consumption in the conventional process (Case i), kWh/t cane | 28 [9] |
| Electricity consumption in vinasse biodigestion, kWh/day | 230 [7] |
| ***Economic assessment*** | |
| Vinasse mass rate, kg/s | 61.95 [1] |
| Vinasse flow rate, $m^3$/s | 0.0679 [1] |
| Operating hours per year, h/year | 4000 [12] |
| Steam consumption at vinasse concentration, kg steam/t cane | 95.3 [1] |
| Bagasse cost, R\$/t bagasse | 60 [13] |
| Distribution losses, % | 10 [14] |
| Electricity selling price, R\$/MWh | 59 [13] |
| $w_{turbine}$, kJ/kg | 610.2 [1] |
| $h_{HP\ steam}$, kJ/kg | 3.360 [1] |
| $h_{boiler\ feedwater}$, kJ/kg | 443.6 [1] |
| Boiler cost ($C_{eq.data}$), R\$ | 23,857,493.26 [15] |
| Boiler capacity ($Cap_{data}$), t/h | 150 [15] |
| $\alpha_{boiler}$ | 0.85 [16] |
| Turbine cost ($C_{eq.data}$), R\$ | 13,523,952.00 [15] |
| Turbine capacity ($Cap_{data}$), MW | 34 [15] |
| $\alpha_{turbine}$ | 0.5 [16] |
| Other capital cost of cogeneration system, (R\$/R\$ of turbine and boiler) | 1.12 [15] |
| Cost of exhaust steam, USD/kg | 0.00553 [2] |
| Fractional interest rate per year, *i* % | 10 [3] |
| Number of years, *n* | 15 [3] |
| Brazilian real exchange rate, R\$/USD | 3.7164 [17] |
| Euro exchange rate, USD/€ | 1.1658 [17] |
| Triple superphosphate in vinasse (46% $P_2O_5$ equivalent), kg/$m^3$ vinasse | 0.435 [18] |
| Potassium chloride in vinasse (60% $K_2O$ equivalent), kg/$m^3$ vinasse | 2.450 [18] |
| Selling price of triple superphosphate, R\$/50 kg triple superphosphate | 29.90 [18] |
| Selling price of potassium chloride, R\$/50 kg potassium chloride | 41.00 [18] |

[1] from simulation; [2] calculated; [3] assumed; [4] Fukushima (2016); [5] Neto & Shintaku (2009b); [6] Neto & Shintaku (2009a); [7] (Salomon et al., 2011); [8] Leme & Seabra (2017); [9] Pina *et al*. (2017); [10] Palacios-Bereche (2011); [11] Avram *et al*. (2009) cited in Lora & Venturini (2012); [12] Ensinas (2008); [13] UDOP (2016); [14] Smith (2005); [15] Agurto (2015); [16] Bejan *et al*. (1996); [17] Banco Central do Brasil (2018); [18] Simões *et al*. (2004)

## 3. RESULTS AND DISCUSSION

The main results of the analysis are reported in Table 4. It can be observed that the additional steam consumption in Case ii, for vinasse concentration purposes, represents an increase of 21.7% of the steam consumption of Case i; while the steam consumption in Case iii was the same as Case i; as no additional steam was considered. Using Configuration 1, Case ii presented an electricity surplus 33.4% higher than that of Case iii. Nevertheless, Case ii had a bagasse surplus 48.4% lower than Case iii. On the other hand, for Configuration 2, the electricity surplus of the incineration and biogas routes was in the same range, resulting in an electricity surplus 8.6% and 6.2% higher than Case i, respectively. Regarding the biogas production, the simulation resulted in 3.65 kg of biogas per tonne of cane processed, which is equivalent to 9.5 $Nm^3$ of biogas per $m^3$ of vinasse produced. This biogas production was higher than the biogas production of the São Martinho plant reported in Poveda (2014) (6 $Nm^3/m^3$ vinasse).

Table 4. Results of energy and economic analyses.

| Parameter | BPST (Configuration 1) | | | CEST (Configuration 2) | | |
|---|---|---|---|---|---|---|
| | Case i | Case ii | Case iii | Case i | Case ii | Case iii |
| **Energy Analysis** | | | | | | |
| Generated steam (at 520°C, 64 bar) (kg/t cane) | 454.39 | 553.39 | 454.39 | 552.24 | 613.01 | 570.10 |
| Generated steam (at 520°C, 64 bar) (t/h) | 227.20 | 276.70 | 227.20 | 276.12 | 306.51 | 285.05 |
| Increasing of generated steam due to new technology implemented (t/h) | - | 49.50 | 0 | - | 30.39 | 8.93 |
| Steam consumption for vinasse concentration (kg/t cane) | - | 95.35 | - | - | 95.35 | - |
| Total steam consumption (kg/t cane) | 437.58 | 532.92 | 437.58 | 437.58 | 532.92 | 437.58 |
| Vinasse[1] used in cogeneration (kg/t cane) | - | 30.14 | - | - | 30.14 | - |
| Biogas used in cogeneration (kg/t cane) | - | - | 3.65 | - | - | 3.65 |
| Bagasse used in cogeneration (kg/t cane) | 209.64 | 226.00 | 200.28 | 253.37 | 253.37 | 253.37 |
| Bagasse surplus (kg/t cane) | 43.73 | 27.37 | 53.09 | - | - | - |
| Electricity surplus (MW) | 26.33 | 35.12 | 26.32 | 39.94 | 43.41 | 42.41 |
| Electricity Surplus (kWh/t cane) | 52.66 | 70.24 | 52.64 | 79.87 | 86.82 | 84.81 |
| Increasing of electricity surplus due to new technology implemented (MW) | - | 8.79 | - | - | 3.47 | 2.47 |
| **Economic assessment** | | | | | | |
| **Capital Cost** | | | | | | |
| *Cogeneration system* | | | | | | |
| Boiler cost for the increasing of generated steam (MMUSD) | - | 2.50 | - | - | 1.65 | 0.58 |
| Turbine for the increasing of electricity surplus (MMUSD) | - | 1.85 | - | - | 1.16 | 0.98 |
| Other capital cost for the cogeneration system (MMUSD) | - | 4.89 | - | - | 3.16 | 1.76 |
| Capital cost for new technology | | | | | | |
| *Concentration – Incineration* | | | | | | |
| Vinasse concentration system (MMUSD) | - | 4.80 | - | - | 4.80 | - |
| *Biodigestion* | | | | | | |
| AD plant (MMUSD) | - | - | 4.16 | - | - | 4.16 |
| Biogas transportation (MMUSD) | - | - | 0.005359 | - | - | 0.005359 |
| H$_2$S removal device (MMUSD) | - | - | 0.02215 | - | - | 0.02215 |
| **Total capital cost (MMUSD)** | **-** | **14.04** | **4.18** | **-** | **10.78** | **7.50** |
| **Annualised capital cost (MMUSD/year)** | **-** | **1.85** | **0.55** | **-** | **1.42** | **0.99** |
| **Operating Cost** | | | | | | |
| *Concentration – Incineration* | | | | | | |

| | | | | | | |
|---|---|---|---|---|---|---|
| Caustic soda for cleaning (MMUSD/year) | - | 0.082 | - | - | 0.082 | - |
| Labour force (MMUSD/year) | - | 0.038 | - | - | 0.038 | - |
| Supplies and administration (MMUSD/year) | - | 0.023 | - | - | 0.023 | - |
| Hydroblasting (MMUSD/year) | - | 0.113 | - | - | 0.113 | - |
| Other labour force and materials (MMUSD/year) | - | 0.131 | - | - | 0.131 | - |
| Steam consumption for vinasse concentration (MMUSD/year) | - | 0.946 | - | - | 0.946 | - |
| *Biodigestion* | | | | | | |
| Operating of AD plant (MMUSD/year) | - | - | 0.104 | - | - | 0.104 |
| Biogas transportation (MMUSD/year) | - | - | 0.000134 | - | - | 0.000134 |
| Operating of $H_2S$ removal device (MMUSD/year) | - | - | 0.028 | - | - | 0.028 |
| Electricity consumption for AD plant (MMUSD/year) | - | - | 0.000736 | - | - | 0.000736 |
| Fertirrigation (MMUSD/year) | - | - | 2.10 | - | - | 2.10 |
| **Total operating cost (MMUSD/year)** | **-** | **1.33** | **2.23** | **-** | **1.33** | **2.23** |
| **Total annualised cost (MMUSD/year)** | **-** | **3.18** | **2.78** | **-** | **2.75** | **3.22** |

MMUSD: million USD; [1] concentrated at 65°Brix

From the results of the economic assessment, when a cogeneration system with back-pressure steam turbine (Configuration 1) is considered, it can be observed that the capital cost of Case ii was, by far, higher than Case iii. The total capital cost of Case ii resulted in a value 235.9% higher than Case iii; owing to the scaling of the cogeneration system which was not necessary in Case iii. Regarding the operating cost, it was Case iii which presented a value 67.7% higher than Case ii, because of the fertirrigation cost which was not considered in Case ii. The total annualised cost indicates that the biodigestion route would be a better alternative for a cogeneration system with Configuration 1, being this cost 12.6% lower than the incineration route. On the other hand, when condensing-extraction steam turbines (Configuration 2) are considered in the cogeneration system, Case ii still presents a higher capital cost, being 43.7% higher than Case iii. The operating cost was the same as the results with Configuration 1. The total annualised cost indicates the incineration route as a more suitable alternative for a cogeneration system with Configuration 2. Regarding the gains due to the selling of electricity surplus (considering a cogeneration system with Configuration 2), Case ii presented a higher value of 0.267 million USD per year, against the 0.190 million USD per year of Case iii. Furthermore, Case ii also presented an additional gain due to the selling of the boiler ashes as biofertiliser, which resulted in 0.597 million USD per year. Owing to the lack of information, this economic analysis was performed in an approximated way, thus, some parameters were not considered, such as the retrofit of the cogeneration boiler to enable it for the burning of concentrated vinasse and biogas in each case. Hence, it is worth mentioning that the biodigestion route can present other advantages, such as the burning of the biogas in internal combustion engines, which are known to have better efficiencies; or the upgrading of the biogas to biomethane for commercialisation, or powering vehicles (Poveda, 2014). Besides, the biogas and biomethane production presents environmental advantages, such as soil recovery (through the use of the biodigested vinasse as a safe biofertiliser), or reduction of greenhouse gases emissions (by replacing fossil fuels with a renewable fuel during energy generation) (ABBM, 2016). Furthermore, a sludge dewatering could be performed to reduce the moisture content of the biodigested vinasse, thus reducing its volume and disposition costs (Rowe & Abdel-Magīd, 1995). Additionally, the separated water could be re-used in the process, or sent to the plantation for irrigation purposes; while the concentrated sludge could also be commercialised as biofertiliser.

A sensitivity analysis was also performed to visualise the changes in Electricity Surplus, when the vinasse LHV and the COD removal efficiency were modified, for cases ii and iii, respectively. Since the vinasse composition varies depending on several factors, various researches have reported different values for the properties of this effluent. In this way, a literature review demonstrated that the vinasse LHV (in dry basis) ranges, approximately, from 11 to 14 MJ/kg (Akram *et al*., 2015; Larsson & Tengberg, 2014; Gallego-Ríos, 2017; Avram *et al*., 2009 *apud* Lora & Venturini, 2012). Meanwhile, several studies regarding vinasse biodigestion have also reported different values for the COD removal efficiency, ranging from 23.6 to 88.5% (Barrera *et al*., 2016; Budiyono *et al*., 2014; de Bazúa *et al*., 1991; Elaiuy, 2016; Coelho *et al*., 2016). Figure 7 (a) presents how the electricity surplus (considering Configuration 2 of the cogeneration system) varies when the vinasse LHV at 65 Brix varies as well. In Fig. 7 (b), the production of biogas (mass rate) and the electricity surplus (considering Configuration 2 of the cogeneration system) varies when the COD removal efficiency also varies.
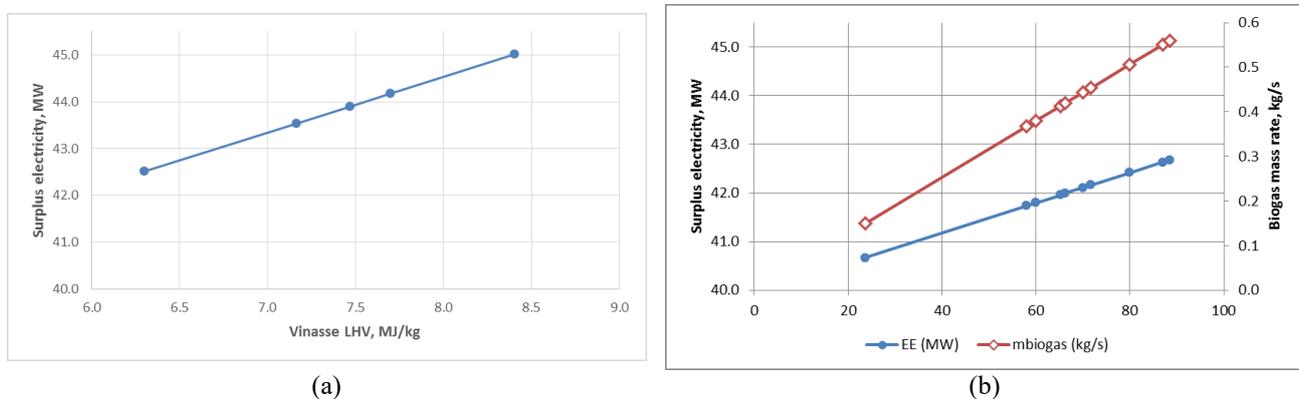


(a)



(b)

Figure 7 (a): Variation of electricity surplus (MW) with the variation of vinasse LHV (MJ/kg) at 65Brix. Figure 7 (b): Variation of electricity surplus (MW) and biogas mass rate (kg/s) with the variation of COD removal efficiency (%).

Finally, a second sensitivity analysis was performed to observe the changes in Total annualising cost, when the bagasse cost and the electricity selling price are modified. The sugarcane bagasse, residue from the sugarcane juice extraction step, was originally considered as useless, and it was burnt in the boiler of the plants to get rid of this residue; or was sold at low prices for animal feed. However, the bagasse became an important energy source, and its selling price rose. Nevertheless, the bagasse cost is rather variable along the time, and prices ranging from 30 R$ per tonne of bagasse up to 150 R$ per tonne of bagasse have been reported in sugarcane-specialised journals (CanaOnline, 2016); agribusiness selling websites (MFRURAL, 2015, 2016), and academic works (Santos, 2015). Regarding the electricity selling price, it is also a variable parameter and depends, in the Brazilian case, on the rain seasons, since most of the Brazilian energy matrix consist of hydraulic power. The literature review revealed values ranging from 23.14 R$/MWh to 140.71 R$/MWh reported in sugarcane-specialised journals (Costa, 2016; Frias *et al*., 2017; NovaCana, 2016; ORPLANA, 2014). Figure 8 (a) presents how the total annualised cost of Case ii (considering Configurations 1 and 2 of the cogeneration system) varies when the bagasse cost varies as well. In Fig. 8 (b), the total annualised cost of Case ii (considering Configurations 1 and 2 of the cogeneration system) varies when the electricity selling price also varies.
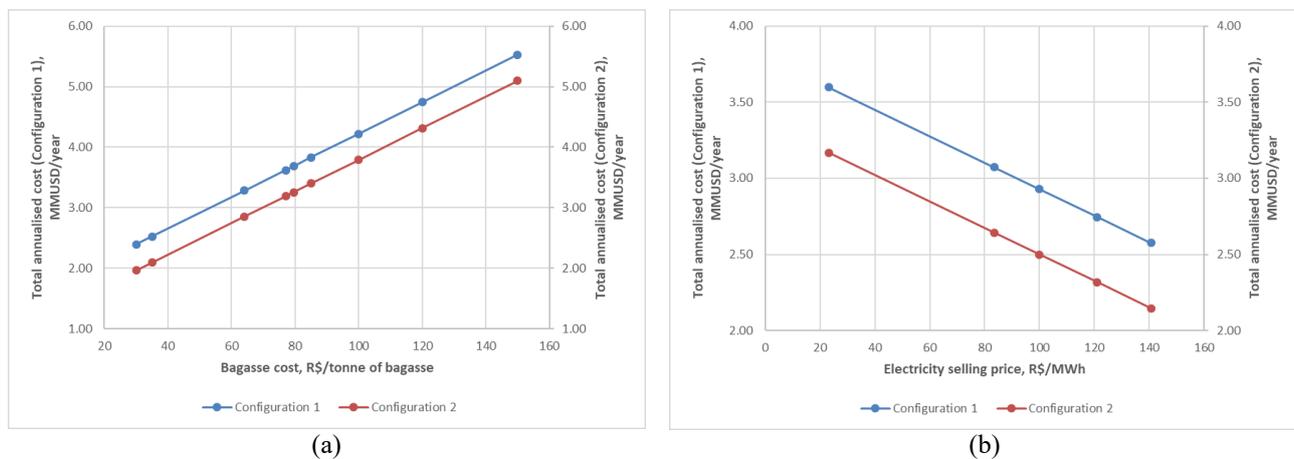


(a)                                                                         (b)

Figure 8 (a): Variation of total annualised cost (MMUSD/year) for Configurations 1 and 2 with the variation of bagasse cost (R$/t bagasse). Figure 8 (b): Variation of total annualised cost (MMUSD/year) for Configurations 1 and 2, with the variation of electricity selling price (R$/MWh).

## 4. CONCLUSIONS

Both alternatives, concentration with subsequent incineration and biodigestion, allow the energy use of vinasse, besides offering advantages to dispose it in a safer way. In the case of concentration with subsequent incineration, the main advantages are the complete removal of the polluting potential, and the significant reduction of the vinasse volume, thus reducing the transport cost of disposition. Moreover, this option improves the availability of water in the factory (water recovered from vinasse), which can be re-used in the process. The biodigestion, on the other hand, can stabilise the organic matter and produce biogas, however, cannot completely eliminate the polluting potential, nor can it reduce the volume of vinasse. Nevertheless, both alternatives offer the possibility of recovering the nutrients of vinasse, through the ashes in the boiler, in the case of the incineration; and through the biodigested vinasse, in the case of the biodigestion. According to the analysis performed, both alternatives proved themselves feasible, since both presented bagasse surplus when using a back pressure steam turbine (Configuration 1) in the cogeneration system; as well as electricity surplus when a condensing-extraction- steam turbine (Configuration 2) was considered. However, Case ii presented the lowest bagasse surplus for Configuration 1; and the highest electricity surplus for Configuration 2, of the analysed cases. In Case iii, higher gains can be observed in bagasse surplus for Configuration 1; while the electricity surplus for Configurations 2, even though lower than Case ii, was still higher than Case i. Regarding the economic assessment, the concentration with incineration of vinasse presented itself as a better option for a cogeneration system with condensing-extraction steam turbines, since it had the lowest annualised cost. On the other hand, when considering a cogeneration system with back-pressure steam turbines, the biodigestion of vinasse was a more suitable option. Nevertheless, since some parameters and costs were disregarded, owing to the lack of information, it is worth mentioning that the biodigestion route can present other advantages, such as the burning of the biogas in internal combustion engines, which are known to have better efficiencies, or the upgrading of the biogas to biomethane for commercialisation. Besides, the environmental advantages of reducing greenhouse gases emissions and soil recovery deserves also to be mentioned.

## 5.  ACKNOWLEDGEMENTS

## 6.  REFERENCES

ABBM – Associação Brasileira de Biogás e Metano (Brazilian Association of Biogas and Methane), 2016. "RenovaBio : Biofuels 2030" (in Portuguese). Santa Cruz do Sul.

Agurto, G., 2015. *Personal communication*. São Paulo.

Akram, M., Tan, C.K., Garwood, R. and Thai, S.M., 2015. "Vinasse - A potential biofuel - Cofiring with coal in a fluidised bed combustor". *Fuel*, Vol 158, p. 1006–1015.

Andrade de, E.T., Carvalho de, S.R.G. and Souza de, L.F., 2009. "Proálcool Program and the Ethanol in Brazil" (in Portuguese). *Engevista*, Vol. 11, p. 127-136.

Banco Central do Brasil, 2018. "Money Exchange" (in Portuguese). 27 Jul. 2018 <https://www4.bcb.gov.br/pec/conversao/conversao.asp>.

Barbosa, V., 2018. "Use of Vinasse in Fertirrigation" (in Portuguese). In *EventosSTAB: IRRIGAÇÃO E FERTIRRIGAÇÃO*. Riberão Preto, Brazil.

Barrera, E.L., Rosa, E., Spanjers, H., Romero, O., De Meester, S. and Dewulf, J., 2016. "A comparative assessment of anaerobic digestion power plants as alternative to lagoons for vinasse treatment: Life cycle assessment and exergy analysis". *Journal of Cleaner Production*, Vol 113, p. 459–471.

Bazúa de, C.D., Cabrero, M.A. and Poggi, H.M., 1991. "Vinasses biological treatment by anaerobic and aerobic processes: Laboratory and pilot-plant tests". *Bioresource Technology*, Vol 35, p. 87–93.

Bejan, A., Tsatsaronis, G. and Moran, M., 1996. *Thermal design and optimization*. New York: John Wiley & Sons.

Budiyono, Syaichurrozi, I. and Sumardiono, S., 2014. "Effect of Total Solid Content to Biogas Production Rate from Vinasse". *International Journal of Engineering, Transactions B: Applications*, Vol 27, p. 177–184.

Cacuro, T.A. and Waldman, W.R., 2015. "Ashes from biomass burning: applications and potential" (in Portuguese). *Revista Virtual de Quimica*, Vol 7, p. 2154–2165.

CanaOnline, 2016. "Sugarcane bagasse price starts to respond" (in Portuguese). 20 Aug. 2018 <http://www.canaonline.com.br/conteudo/preco-do-bagaco-de-cana-comeca-a-reagir.html#.W3wsS-hKiUl>

CETESB – Environmental Company of the State of São Paulo, 2015. "Technical Standard P4.231. Vinasse – Criteria and procedures for its application in agricultural land" (in Portuguese). SP, Brazil.

Cheremisinoff, N.P., 1996. *Biotechnology for waste and wastewater treatment*. Noyes Publications, Westwood, New Jersey, U.S.A.

Christofoletti, C.A., Escher, J.P., Correia, J.E., Marinho, J.F.U. and Fontanetti, C.S., 2013. "Sugarcane vinasse: Environmental implications of its use". *Waste Management* Vol. 33, p. 2752–2761.

Citrotec, 2012. "Vinasse Concentration" (in Portuguese). 13 SBA – A Plant in numbers. 20 Jan. 2018 <http://www.stab.org.br/13_sba_palestras/24_citrotec_concentracao_vinhaca.pdf>.

Coelho, J.M., 2017. "Presentation regarding the EPE and the RenovaBio Program" (in Portuguese). *V Symposium of the Post-Graduation Course in Energy*, Federal University of ABC. Santo André, SP, Brazil.

Coelho, W.L.V., Silva da, F.S., Dallacort, R. and Carneiro, P.A.V., 2016. "Analysis of the electric energy generation potential from the sugar and ethanol industrial residues in the state of Mato Grosso in different productive scenarios" (in Portuguese). *Revista Brasileira de Energias Renováveis*, Vol 5, p. 332–351.

Cortez, L.A.B., Rossell, C.E.V., Jordan, R.A., Leal, M.R.L.V. and Lora, E.E.S., 2010. "R&D Needs in the industrial production of vinasse". In: Cortez, L.A.B. (coord.) *Sugarcane Bioethanol – R&D for Productivity and Sustainability*, p. 619–636. Blucher.

Costa, L., 2016. "Energy spot price in the Southeast rises 49% even though an improvement in the raining season" (in Portuguese). 20 Aug. 2018 <https://www.novacana.com/n/cogeracao/preco-spot-energia-sudeste-sobe-melhoria-chuvas-290816/>

Elaiuy, M.L.C., 2016. *Anaerobic biodigestion of sugarcane vinasse: approach of the ADM1 model and efficiency of biodegradation in soil* (in Portuguese). PhD. Thesis, State University of Campinas, Campinas, SP., Brazil.

Ensinas, A.V., 2008. *Thermal integration and thermoeconomic optimisation applied to the sugar and ethanol industrial process from sugarcane* (in Portuguese). PhD. Thesis, State University of Campinas, Campinas, SP., Brazil.

Flin, D., 2009. *Cogeneration: A user's guide*. The Institution of Engineering and Technology, London, UK.

Flores-Zavala, B.A., 2016. *Benefiting from the biogas produced in anaerobic biodigesters for producing biomethane and electric energy* (in Portuguese). Master's Thesis, Federal University of ABC, Santo Andre, SP, Brazil.

Freire, W.J. and Cortez, L.A.B., 2000. *Vinasse from sugarcane* (in Portuguese). Livraria e Editora Agropecuária Ltda, Guaíba, RS, Brazil.

Frias, M.C., Gutierrez, F., Hirata, T. and Utsumi, I., 2017. "Cogen asks for a reference price of 300 R$/MWh for sugarcane electricity" (in Portuguese). 20 Aug. 2018 <https://www.novacana.com/n/cogeracao/cogen-preco-referencia-

eletricidade-cana-de-acucar-170417/>

Fuess, L.T., de Araújo Júnior, M.M., Garcia, M.L. and Zaiat, M., 2017. "Designing full-scale biodigestion plants for the treatment of vinasse in sugarcane biorefineries: How phase separation and alkalinization impact biogas and electricity production costs?". *Chemical Engineering Research and Design*, Vol 119, p. 209–220.

Fuess, L.T. and Zaiat, M., 2018. "Economics of anaerobic digestion for processing sugarcane vinasse: Applying sensitivity analysis to increase process profitability in diversified biogas applications". *Process Safety and Environmental Protection*, Vol 115, p. 27–37.

Fukushima, N.A., 2016. *Energy analysis of the integration of a vinasse concentration and incineration system into a sugar and ethanol plant* (in Portuguese). Master's Thesis, Federal University of ABC, Santo Andre, SP, Brazil.

Gallego-Ríos, J.M., 2017. *Effect of processing conditions on the properties of briquettes produced from residues from the ethanol production: Characterisation and analysis of the thermogravimetric behaviour* (in Portuguese). Master's Thesis, Federal University of ABC, Santo Andre, SP, Brazil.

Larsson, E. and Tengberg, T., 2014. *Evaporation of Vinasse : Pilot Plant Investigation and Preliminary Process Design*. Master's Thesis, Chalmers University Of Technology, Göteborg, Sweden.

Leme, R.M. and Seabra, J.E.A., 2017. "Technical-economic assessment of different biogas upgrading routes from vinasse anaerobic digestion in the Brazilian bioethanol industry". *Energy*, Vol 119, p. 754–766.

Lora, E.E.S. and Venturini, O.J., 2012. *Biofuels: Volume 2* (in Portuguese). Rio de Janeiro: Editora Interciência Ltda.

Mello de, A.G.B., 2012. *Reduction and recycling of water in the ethanol production process: A case study* (in Portuguese). MTA's monograph, Federal University of São Carlos, Piracicaba, Brazil.

MFRURAL, 2015. "Cane bagasse" (in Portuguese). 20 Aug. 2018 <http://www.mfrural.com.br/detalhe/bagaco-de-cana-promocao-espetacular-apenas-69.00-a-tonelada-sul-de-goias.-oferta-192396.aspx>.

MFRURAL, 2016. "Sugarcane bagasse" (in Portuguese). 20 Aug. 2018 <http://www.mfrural.com.br/detalhe/bagaco-de-cana-de-acucar-174373.aspx>.

Neto, A.E. and Shintaku, A., 2009a. "6. Good Industrial Practices". In: *Handbook of water reuse and conservation in the sugar-energy agro-industry* (in Portuguese). National Agency of Water, Environment Ministry, p. 181–256. Brasília.

Neto, A.E. and Shintaku, A., 2009b. 5. "Use and reuse of water and effluent generation". In: *Handbook of water reuse and conservation in the sugar-energy agro-industry* (in Portuguese). National Agency of Water, Environment Ministry, p. 67–180. Brasília.

NovaCana, 2016. "Energy price rises in free market and encourages interested generation companies in the long run" (in Portuguese). 20 Aug. 2018 <https://www.novacana.com/n/cogeracao/preco-energia-sobe-mercado-livre-anima-geradoras-longo-prazo-230816/>.

ORPLANA - Organisation of sugarcane growers of the Centre-South Brazilian Region, 2014. "With a high price, energy generation rate of biomass plants increases" (in Portuguese). 20 Aug. 2018 <http://www.orplana.com.br/novosite/informa.php?not=1342>.

Palacios-Bereche, R., 2011. *Modelling and energy integration of the ethanol production process from sugarcane biomass* (in Portuguese). PhD. Thesis, State University of Campinas, Campinas, SP., Brazil.

Penatti, C.P. and Donzelli, J.L., 2000. "Use of vinasse in sugarcane crops (in Portuguese). Cooperativa de produtores de cana, açúcar e álcool do Estado de São Paulo LTDA. – COPERSUCAR. Piracicaba, SP, p.1-22.

Pina, E.A., Palacios-Bereche, R., Chavez-Rodriguez, M.F., Ensinas, A.V., Modesto, M. and Nebra, S.A., 2017. "Reduction of process steam demand and water-usage through heat integration in sugar and ethanol production from sugarcane - Evaluation of different plant configurations". *Energy,* Vol. 138, p. 1263–1280.

Poveda, M.M.R., 2014. *Economic and environmental analysis of the vinasse processing with energy use*. Master's Thesis, University of São Paulo, SP, Brazil.

Rowe, D.R. and Abdel-Magīd, I.M., 1995. *Handbook of wastewater reclamation and reuse*. USA: Lewis Publishers.

Salomon, K.R., Lora, E.E.S., Rocha, M.H. and Olmo del, O.A., 2011. "Cost calculations for biogas from vinasse biodigestion and its energy utilization". *Sugar industry* Vol. 136, p. 217–223.

Santos, M.A.S., 2015. *What to do with the sugarcane bagasse? An approach of the real option theory applied to ethanol and sugar producing plants in the Piracicaba region* (in Portuguese). Master's Thesis, Economy School of São Paulo, Fundação Getúlio Vargas, São Paulo, Brazil.

Simões, C.L. do N., Sena, M.E.R. de, and Campos, R. de., 2004. "Study of the economic feasibility of vinasse concentration through reverse osmosis" (in Portuguese). In *Proceedings of the XXIV Encontro Nacional de Engenharia de Produção* (pp. 5286–5293). Florianópolis, SC, Brasil.

Smith, R., 2005. *Chemical Process Design and Integration*. *John Wiley & Sons, Ltd*. England: John Wiley & Sons, Ltd.

Sosa-Arnao, J. H., 2018. *Personal communication*. São Paulo.

UDOP-União dos Produtores de Bioenergia, 2016. "Sugarcane" (in Portuguese). 28 Nov. 2016 <http://www.udop.com.br/index.php?item=noticias&cod=1138389>.

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