Energy and Exergy Cost Analysis of Two Different Routes for Vinasse Treatment with Energy Recovery

Milagros Cecilia Palacios-Bereche, Reynaldo Palacios-Bereche
and Silvia Azucena Nebra

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Milagros Cecilia Palacios-Bereche[a], Reynaldo Palacios-Bereche[b] and Silvia Azucena Nebra[c]

[a] *Energy Engineering Modeling and Simulation Laboratory, Federal University of ABC, Santo André, S.P., Brazil, milagros.palacios@ufabc.edu.br*
[b] *Federal University of ABC, Santo André, S.P., Brazil, reynaldo.palacios@ufabc.edu.br*
[c] *Federal University of ABC, Santo André, S.P., Brazil/ University of Campinas, Campinas, S.P., Brazil, silvia.nebra@ufabc.edu.br,* ***CA***

Abstract:

The vinasse, produced as the bottom product of the distillation column of the ethanol production process, is the main liquid residue of this industry. It is a dark brown liquid of acidic nature and high organic matter content, thus making it a polluting effluent. Currently, it is used to fertilise and irrigate sugarcane fields, taking advantage of its nutrients and high water content. However, its disposition is still a problem because of its high production rate, which ranges from 10 to 15 litres of vinasse per litre of ethanol produced. This way, this work addresses the vinasse problem by a preliminary exergy cost analysis of three alternatives for vinasse disposition with energy recovery and a Base Case for comparison purposes; being the analysed cases: i) a Base Case (conventional production process), ii) the vinasse concentration with subsequent incineration, iii) the vinasse biodigestion with burning of the produced biogas in the boiler of the cogeneration system, and iv) the vinasse biodigestion and subsequent biogas purification aiming at the biomethane production. The preliminary results show the clean biogas of Case iii as the product with the highest unit exergy cost (7.03), followed by the biomethane of Case iv (with a unit exergy cost of 6.95), indicating that important irreversibilities are associated to the biogas production route.

Keywords:

Vinasse, Concentration, Incineration, Biodigestion, Exergy cost.

1. Introduction

Brazil is the biggest producer of sugarcane in the world [1]; and the sugar and ethanol industry is one of the most important sectors of the national economy. The Brazilian ethanol owes its success to its economic competitiveness, which was achieved through economies of scale and technological advances over time [2]. Nowadays, the Brazilian government is presenting the RenovaBio Program, seeking to expand the biofuel production [3], being the ethanol among the biofuels contemplated. Nonetheless, the main liquid residue of this production process, or vinasse, still represents a problem for the industry, because of its difficult and costly disposition due to the large generated volume. Furthermore, with an increasing ethanol production, encouraged by the RenovaBio Program, the vinasse generated will increase as well.

The vinasse, produced as the bottom product of the distillation column, is a dark brown liquid of acidic nature and high organic matter content, thus making it a polluting effluent. However, its solid content is also rich in nutrients such as potassium, sodium, calcium, phosphorous, manganese and nitrogen, among others, which can be used as fertilisers. This way, the fertirrigation, current vinasse disposition, takes advantage of the nutrients in the solid content, and the high water content to fertilise and irrigate at the same time by aspersing the vinasse over the sugarcane crops [4]. Still, the main problem for its disposition is the high production rate, which ranges from 10 to 15 litres of vinasse per litre of ethanol produced [4].

This way, this work addresses the vinasse problem by a preliminary exergy cost analysis of three alternatives for vinasse disposition with energy recovery. Being these alternatives: a) vinasse concentration with subsequent incineration, b) vinasse biodigestion with burning of the produced biogas in the boiler of the cogeneration system, and c) vinasse biodigestion with subsequent biogas purification aiming at the production of biomethane.

This type of analysis (exergoeconomics) is a tool to identify the location, magnitude and source of thermodynamic losses (irreversibilities) in an energy system. Furthermore, it calculates the cost associated with the exergy destruction and exergy losses; besides assessing the production costs of each product in an energy-conversion system that has more than one product. The exergoeconomics is also used to compare technical alternatives and facilitates feasibility and optimization studies [5].

2. Processes description and cases

2.1. Case i (Base Case): Conventional ethanol, sugar and electricity production process

A conventional ethanol, sugar and electricity production process was considered as a Base Case, for comparison purposes. The conventional process comprises the following sub-systems: sugarcane cleaning and juice extraction, juice treatment for sugar and ethanol production routes, juice concentration, sugar crystallisation, sugar drying, must preparation and cooling, fermentation, and distillation and rectification. The Base Case was assumed as a medium size plant processing 500 tonnes of sugarcane per hour, and consuming saturated steam at 2.5 bar for thermal requirements. Figure 1 presents a simplified flowsheet of the Base Case.

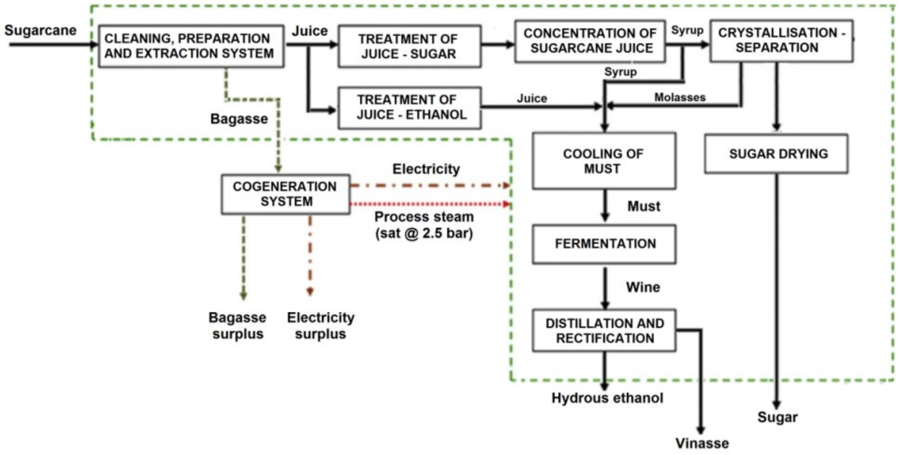

Fig. 1. Flowsheet of Case i: Base Case. Modified from [6].

2.2. Case ii: Vinasse concentration with subsequent incineration

The vinasse concentration and incineration route, or Case ii, was considered as a Base Case coupled to a vinasse concentration system, sending the concentrated vinasse to the boiler of the cogeneration system. A seven-effect evaporation system and a concentration up to 65 Brix was considered, as some manufactures already commercialise this type of vinasse evaporators [7]. Figure 2 shows the simplified flowsheet of Case ii, while Figure 3 presents a simplified scheme of the vinasse concentration system.

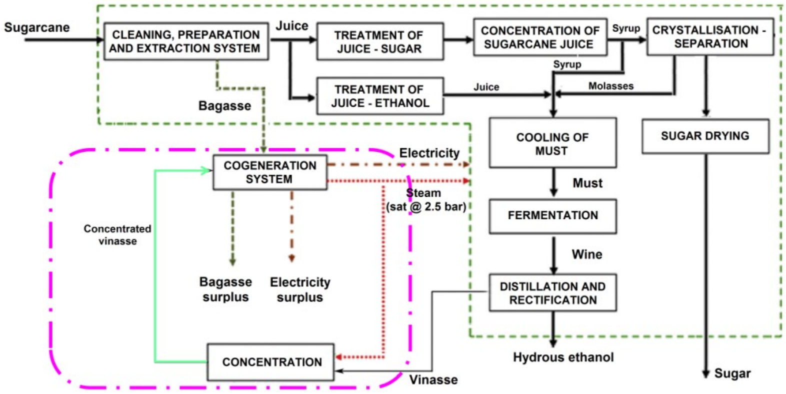

Fig. 2. Flowsheet of Case ii: Base Case + vinasse concentration system. Modified from [6].

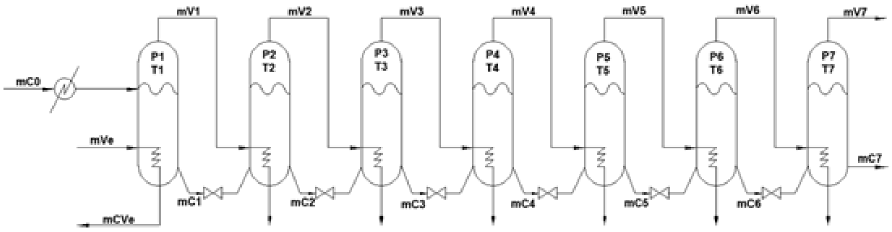

Fig. 3. Scheme of the seven-effect evaporation system for vinasse.

2.3. Case iii: Biodigestion of vinasse

This case assumes the vinasse biodigestion to produce biogas, which is send to be burnt in the boiler of the cogeneration system; as can be observed in Figure 4. Mass and energy balances were carried out utilising the software EES® according to [8]. The biogas cleaning was assumed to be carried out in a desulphurisation system according to the THIOPAQ process. The parameters and guidelines for biogas production and desulphurisation were taken from [9]. Figure 4 shows the flowsheet for Case iii.

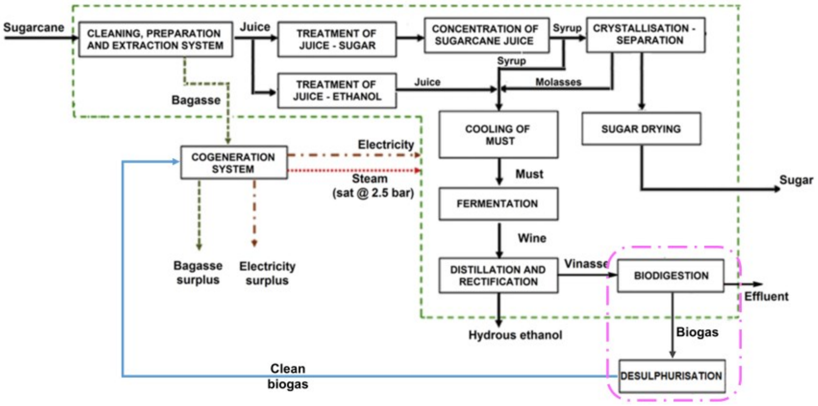

Fig. 4. Flowsheet of Case iii: Base Case + biodigestion + desulphurisation systems. Modified from [6].

2.4. Case iv: Biomethane production from vinasse biodigestion

Finally, Case iv assumed a Base Case coupled to a biodigestion system, a desulphurisation system for biogas cleaning, and a purification system for biomethane production. In the same way as in Case iii, the THIOPAQ process was assumed for the desulphurisation process, while the water scrubbing process was selected for biogas purification The parameters and guidelines for biogas production, desulphurisation, and biogas purification were taken from [9]. Figure 5 depicts the flowsheet of Case iv.

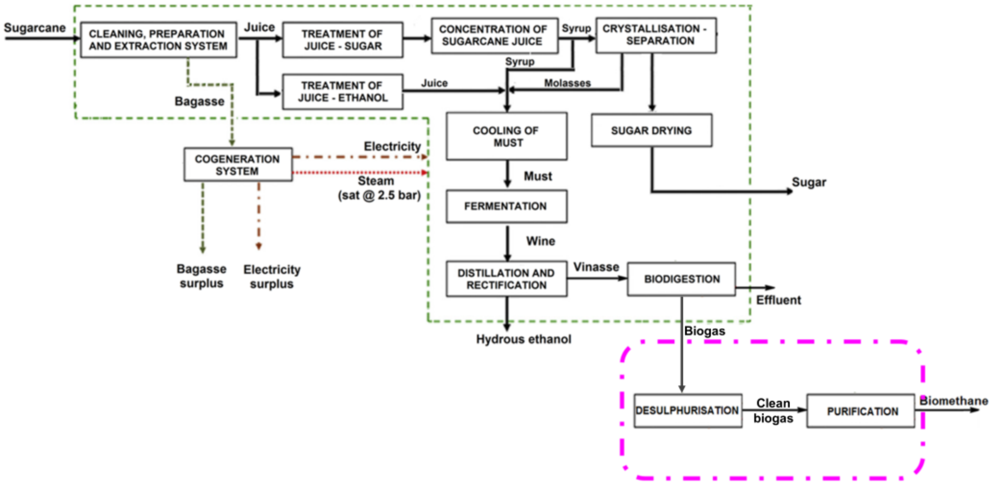

Fig. 5. Flowsheet of Case iii: Base Case + biodigestion + dessulphurisation + purification systems. Modified from [6].

Figure 6 shows the flowsheet for the biogas purification system with water scrubbing according to [10].

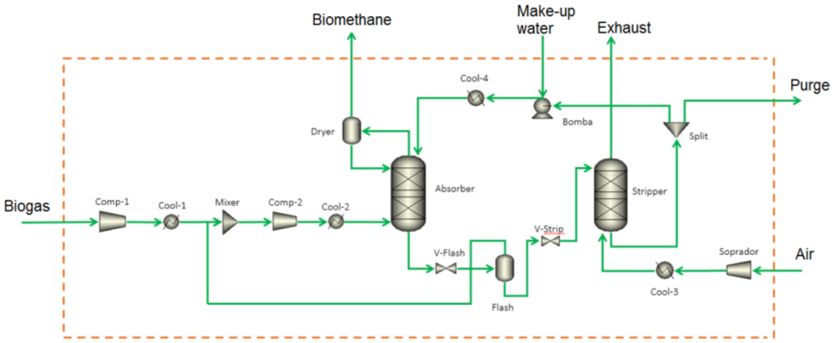

Fig. 6. Flowsheet of purification system with water scrubbing. Source [9].

2.5. Cogeneration system

In sugarcane-processing plants, a power steam cycle, using sugarcane bagasse as fuel, is commonly used as the cogeneration system. This cogeneration system was based on a Rankine cycle, producing steam at 65 bar and 520°C [11]. It supplies the requirements of steam, electricity and/or mechanical work to the plant. A configuration assuming condensing-extraction steam turbines (CEST), burning all the available bagasse to maximise the electricity surplus, was adopted. Figure 7 presents the scheme of the configuration system adopted.

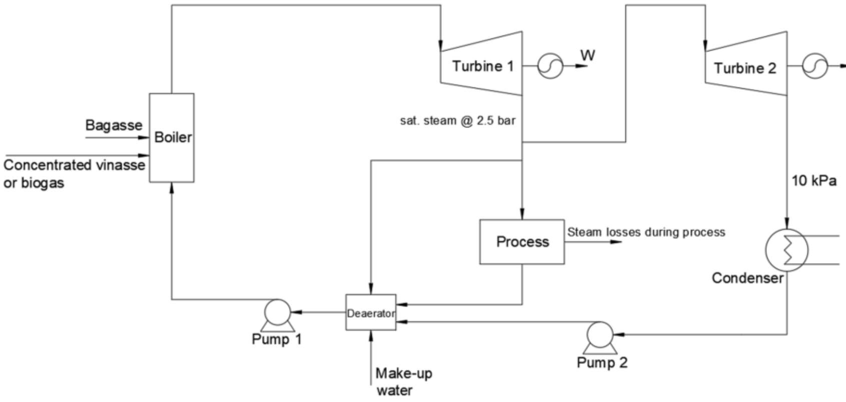

Fig. 7. Configuration of the cogeneration system (CEST).

3. Methodology

The main steps performed in the present work are listed below:

- Modelling and simulation of conventional production process (Base Case), alternative technologies for vinasse energy use (Cases ii, iii and iv), and cogeneration system;
- exergy analysis;
- exergy cost assessment.

3.1. Conventional process, alternative technologies, and cogeneration system simulation

The software Aspen Plus™ V9 was used to simulate the conventional process of sugar, ethanol and electricity production, thus performing mass and energy balances. The simulation was performed according to previous studies [8,12]. Data from the literature were collected to perform the process simulation, and the guidelines from [13–15] were followed. A flowsheet diagram of the simulated conventional process is presented in Figure 8.

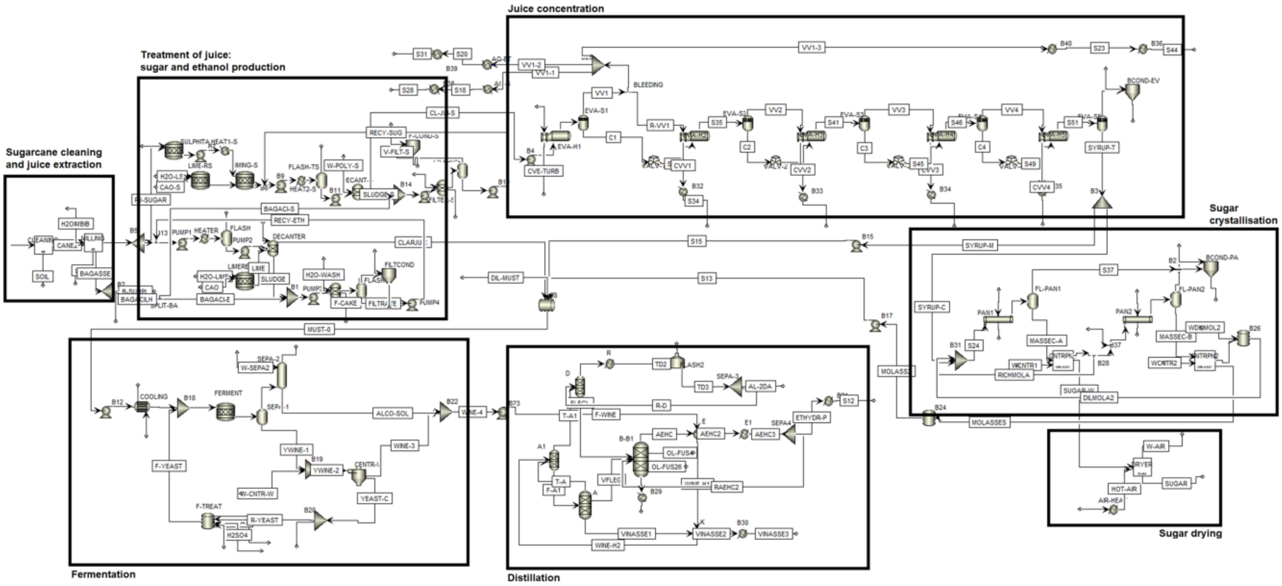

Fig. 8. Sugar and ethanol conventional production process simulated in Aspen Plus™ V9

The alternative technologies considered in this study, comprising vinasse concentration, vinasse biodigestion, biogas cleaning and biomethane production, were simulated through mass and energy balances using the software EES®; because of its faster convergence and ease of use.

The vinasse concentration and biodigestion were modelled according to previous works [8,12], while the biogas cleaning and biomethane production followed the guidelines presented in [9].

A Rankine cycle was used to model the cogeneration system, considering a steam production at 65 bar and 520°C [11].

The main parameters for the process simulation are presented in Table 1.

Table 1. Main parameters for process simulation

Parameter	Value
Conventional process simulation	
Sugarcane processed, t cane/h	500 (1)
Produced sugar, t/h	34.2 (2)
Produced hydrous ethanol, m^3/h	21.1 (2)
Total produced bagasse (50% of humidity); t/h	136 (2)
Steam consumption (sat. @ 2.5 bar) in conventional process, kg/t cane	429.5 (2)
Electricity consumption in conventional process, kWh/t cane	28 (1)
Vinasse concentration	
Initial brix of vinasse, %	4.29 (2)
Final brix of vinasse, %	65 (3)
Effect pressures of vinasse concentration system (3)	
Effect 1, bar	2.139
Effect 2, bar	1.788
Effect 3, bar	1.449
Effect 4, bar	1.12
Effect 5, bar	0.802
Effect 6, bar	0.496
Effect 7, bar	0.2
Vinasse biodigestion	
Vinasse COD, kg/m^3	23.8 (4)
COD removal efficiency, %	80 (5)
Biogas conversion factor, Nm^3_{biogas}/kg COD	0.5 (5)
Biogas density, kg/Nm^3	0.784 (6)
Electricity consumption in biodigestion, kWh/day	230 (6)
Biogas composition (7)	
CH_4, %mol (dry basis)	60
CO_2, %mol (dry basis)	38.1
H_2S, %mol (dry basis)	1.9
H_2O, % mol	5.5
Biogas cleaning	
CH_4 concentration increase, %	10.33 (8)
H_2S removal efficiency, %	99.89 (8)
Electricity consumption, kWh/Nm^3_{biogas}	0.024 (8)
Biomethane production	
Methane recovery efficiency, %	99.77 (8)
CO_2 separation efficiency, %	98 (8)
$V_{air}/V_{clean\ biogas}$	2.026 (8)
Water loss, %	2.4 (9)
Electricity consumption, kWh/$Nm^3_{clean\ biogas}$	0.2374 (8)
Cogeneration	
Boiler pressure, bar	65 (10)
Boiler temperature, °C	520 (10)
Process steam pressure, bar	2.5 (2)
Bagasse LHV (with 50% of humidity), MJ/kg	7.645 (11)
Vinasse HHV (dry), MJ/kg	13.2 (12)
Boiler efficiency, %	85 (13)
Turbine efficiency, %	80 (14)
Pump efficiency, %	80 (14)

(1) Pina et al. [6]; (2) from simulation; (3) Fukushima [16]; (4) Elia Neto and Shintaku [17]; (5) Elia Neto and Shintaku [18]; (6) Salomon et al. [19]; (7) Leme and Seabra [20]; (8) Flores-Zavala [9]; (9) Cozma et al. [21]; (10) Sosa-Arnao [11]; (11) calculated; (12) Gallego-Ríos [22]; (13) Cortes-Rodríguez et al. [23]; (14) Ensinas [15]

3.2. Exergy calculation

The exergy of each stream of the evaluated processes was calculated according to previous studies [8,12]. A reference level was chosen at 25°C and 1.01325 bar, according to [24]. The total thermal exergy (ex_{tot}) was calculated as the sum of the physical (ex_{phy}) and chemical (ex_{ch}) exergies [24]:

$$ex_{tot} = ex_{phy} + ex_{ch} . \quad (1)$$

The physical exergy was calculated according to (2), neglecting the potential and kinetic components:

$$ex_{phy} = h - h_0 - T_0 (s - s_0) , \quad (2)$$

where the subscript 0 indicated the reference level.

The chemical exergy is calculated, generally, considering the activity of the stream, as can be observed in (3), considering the standard chemical exergy of pure components (first term) and the losses of chemical exergy due to the dissolution process (second term), according to [24]:

$$ex_{ch} = \left(\frac{1}{\overline{M}} \right) \cdot \left[\sum_{i=1}^{n} y_i \cdot ex_i^{\circ} + \overline{R}_u \cdot T_0 \sum_{i=1}^{n} y_i \cdot \ln(a_i) \right] . \quad (3)$$

Nevertheless, other approaches were followed for certain streams. Thus, when sucrose-containing streams were contemplated (sugarcane, bagasse, juice, syrup, molasses, sugar), the specific exergy was calculated according to the guidelines presented in [25]. On the other hand, for ethanol-containing streams, the guidelines in [26] were followed. The vinasse, as it is produced and concentrated, was considered as a technical fuel that contains small amounts of sulphur and ashes [24] to calculate its chemical exergy, as in previous studies [8,12]. The streams participating in the biodigestion route (biogas, clean biogas and biomethane) were considered as ideal solutions.

3.2. Exergy cost assessment

Since the exergy is an objective measure of the thermodynamic value of an energy carrier, it is also closely related to the economic value of said carrier, because users pay for the potential of energy to cause changes [5]. Thus, the exergoeconomic approach was utilised, since it integrates thermodynamic and economic analysis through the exergy costing, which is the assignment of costs to the exergy content of an energy carrier [5]. The Theory of Exergetic Cost [27] was followed to perform the exergy cost assessment in this study.

An exergetic cost balance was performed in each sub-system of the production process of the proposed cases (4), to calculate the exergetic cost of a flow:

$$\sum \dot{B}_{in} = \sum \dot{B}_{out} , \quad (4)$$

where $\dot{B}$ represents the exergetic cost of each flow that enters (*in*) to, and goes out (*out*) from the control volume.

According to [27], the exergetic cost of a flow ($\dot{B}$) is defined as the amount of exergy required to produce said flow (5):

$$\dot{B}_i = k_i \cdot \dot{E}x_i , \quad (5)$$

where the exergetic cost of an *i* stream is determined by its unit exergetic cost (k_i) and its total exergy $(\dot{E}x_i)$. The total exergy of a stream is calculated by its specific exergy (calculated in the previous section) and the mass flow of the stream, which is given by the process simulation.

Applying (4) to all the sub-systems of the production processes of all the considered cases results in a system of linear equations, where the unit exergetic cost (k_i) remains unknown. Thus, assumptions were made by following the propositions of the Theory of the Exergetic Cost [27], resulting in additional equations that are required to resolve the equation system.

- A unitary value is assigned as the unit exergy cost (k_i) of external inputs (sugarcane, freshwater, chemicals).

$$k_{external\,input} = 1 \quad .(6)$$

- By-products of the control volume are assigned a unit exergy cost (k_i) equal to the input (P4a).

$$k_{by-product} = k_{input} \quad . \qquad (7)$$

- If a control volume has two or more product streams, then the same unit exergy cost (k_i) is assigned to all of them (P4b).

$$k_{product1} = k_{product2} = \ldots = k_{productn} \quad . \qquad (8)$$

- The unit exergy cost (k_i) of the energy carrier (steam, condensates, vapour bleeds) is determined during its generation (at the boiler of the cogeneration system) and do not change throughout the process.

$$k_{live\,steam} = k_{process\,steam} = k_{condensates} = k_{vapour\,bleeds} \quad .(9)$$

- The cost of the irreversibility associated with the operation of the condenser in the cogeneration system, is added to the turbine control volume, thus increasing the unit exergy cost (k_i) of the electricity.

4. Results and discussion

The results of the main products and by-products obtained from the simulation of the evaluated cases are presented in Table 2.

Table 2. Main results from simulations

Product/By-product	***Case i:*** ***Base Case***	***Case ii: Conc. + Incineration***	***Case iii:*** ***Biogas+ burning***	***Case iv: Biomethane***
Sugarcane rate, t/h	500	500	500	500
Sugar, kg/t cane	68.4	68.4	68.4	68.4
Hydrous ethanol, l/t cane	42.1*	42.1*	42.1*	42.1*
Bagasse produced in mills, kg/t cane (50% of moisture content)	272	272	272	272
Vinasse, l/t cane	495.6**	495.6**	495.6**	495.6**
Vinasse/ethanol ratio	11.7	11.7	11.7	11.7
Concentrated vinasse, kg/t cane	-	29.9***	-	-
Biogas production, Nm^3/t cane	-	-	4.72	4.72
Biogas mass flow, kg/t cane	-	-	3.6	3.6
Biodigested vinasse, kg/t cane	-	-	449	449
Clean biogas, kg/t cane	-	-	3.14	3.14
Biomethane, kg/t cane	-	-	-	1.26
Electricity surplus, kWh/t cane	81.2	89.7	85.7	80.4

* at 35°C; ** at 74.9°C; *** at 65 brix

Table 3 presents the results of the energy analysis of the cogeneration system. It can be observed that Case ii and Case iii present higher electricity production than the other cases, being Case ii the one with the highest value. This can be explained because of the additional fuels (concentrated vinasse and clean biogas) that are burned in the boiler, which increase the generated steam (the generated steam of Case ii being 12% higher than the Base Case and Case iv, while an increase of 2.9% for Case iii was obtained), thus increasing the amount of steam that is expanded in the turbine. Moreover, the energy contained in concentrated vinasse was higher, allowing a higher steam production (being the generated steam of Case ii 8.8% higher than Case iii).

On the other hand, since in Case iv the biomethane is considered as an added value product suitable for sale, the only fuel used in the cogeneration system is the bagasse. For this reason, the amount of generated steam is the same as in the Base Case, and the electricity surplus resulted in a lower value because of the additional electricity consumption for this process. Nevertheless, this decrease in electricity surplus is not significant, being only 0.98% lower than the Base Case.

The electricity consumption in Cases iii and iv was higher in comparison to the others cases (i and ii) because of the consumption of the biodigestion, desulphurisation and purification processes, however, this increase was not significant (0.02 kWh/t of cane in Case iii and 0.71 kWh/t of cane in Case iv).

Table 3. Main results – Cogeneration: CEST Configuration

Parameter	***Case i:* *Base Case***	***Case ii:* *Conc. + Incineration***	***Case iii:* *Biogas + burning***	***Case iv:* *Biomethane***
Steam: Generation and consumption				
Generated steam in boiler [1], kg/t cane	552.2	618.6	568.3	552.2
Increasing of generated steam [1] due to new technology, kg/t cane	-	66.4	16.1	-
Steam consumption [2] for vinasse concentration, kg/tcane	-	96.8	-	-
Total steam consumption [2], kg/t cane	429.5	526.2	429.5	429.5
Fuel used in cogeneration system				
Bagasse, kg/t cane	253.4	253.4	253.4	253.4
Vinasse [3], kg/t cane	-	29.9	-	-
Clean biogas kg/t cane	-	-	3.14	-
Electricity				
Electricity consumption; kWh/t cane	28	28	28.02	28.71
Electricity surplus, kWh/t cane	81.2	89.7	85.7	80.4

[1] at 520°C and 65 bar; [2] saturated at 2.5 bar; *** at 65 brix

Table 4 and Figure 9 show the main results of the exergy cost assessment, presenting the unit exergy cost of the main products of the evaluated cases. The unit exergy costs for electricity resulted in the range of 4.2 and 4.9; while the unit exergy costs for steam resulted between 3.4 and 3.9.

Regarding the main products, Case ii presented slightly higher unit exergy costs in comparison to the Base Case, because of the higher irreversibilities present in the first one. Furthermore, the unit exergy costs of the products in Case iii were even higher than in Case ii, because the clean biogas used in boiler has a significant unit exergy cost (7.03).

The clean biogas unit exergy cost in Case iii resulted in a higher value than the respective cost of the same product in Case iv, because of the high electricity cost in Case iii.

Regarding the results of Case iv, the unit exergy costs of conventional products resulted the same as in the Base case. The most expensive product in this case is the biomethane, with an exergy cost of 6.9, followed by the electricity and steam, these results show the influence of irreversibilities caused by the biochemical reactions inherent to the biogas production.

Regarding the unit exergy cost of the vinasse that leaves the distillation column, Cases i and iv presents the same value, since both cases presented the same electricity and steam costs, as previously explained. On the other hand, it can be observed that the vinasse unit exergy cost in Cases ii and iii present a higher value; because larger costs of inputs process: electricity and steam, due to additional fuels (concentrated vinasse and biogas), with larger unit exergy costs, are used in boilers.

It is worth mentioning that the cost distribution of The Theory of Exergetic Cost [27], penalise the products at the end of the productive process, accumulating exergy cost [28]. Such is the case of the biodigestion route, whose products (biogas, clean biogas and biomethane) carry not only the irreversibilities of their respective unit (biodigestion, desulphurisation and purification), but also the irreversibilities of the rest of the process in the vinasse.

Table 4. Main results – Exergy cost assessment

Product	***Case i:*** ***Base Case***	***Case ii: Conc.-Incin.***	***Case iii:*** ***Biogas + burning***	***Case iv: Biomethane***
Ethanol	2.06	2.10	2.14	2.06
Sugar	1.55	1.57	1.61	1.55
Vinasse (as produced)	1.80	1.82	1.84	1.80
Concentrated vinasse (65 brix)	-	1.97	-	-
Biogas	-	-	6.37	6.21
Clean biogas	-	-	7.03	6.85
Biomethane	-	-	-	6.95
Steam	3.42	3.68	3.90	3.42
Electricity	4.29	4.58	4.90	4.29

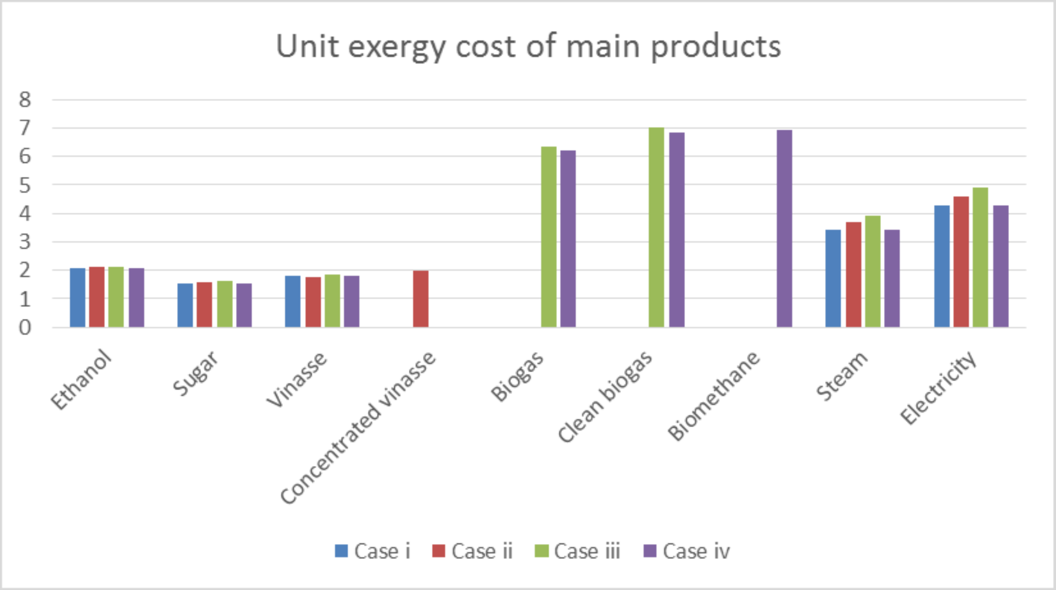

Fig. 9. Unit exergy cost of main products.

5. Conclusions

This preliminary exergy cost analysis allowed the comparison of different routes of vinasse treatment aiming at its energy recovery.

This analysis allowed to visualise and compare production costs, in terms of exergy, of each product of the sugarcane processing plant. The results presented the sugar as the cheapest product, followed by the ethanol, while the clean biogas of Case iii was the most expensive. In addition, this preliminary exergy cost analysis also indicates the impacts in unit exergy costs caused by the introduction of alternative process to treat vinasse with energy recovery.

Furthermore, the results showed that the production of biomethane, as a new product, would be preferable than the production of biogas to be burned in a boiler for electricity production.

Acknowledgments

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Appendix A

Figures A.1 and A.2 present the flow sheet diagrams of the conventional production process (A.1) and the vinasse concentration and biogas routes (A.2) depicting the participating process streams.

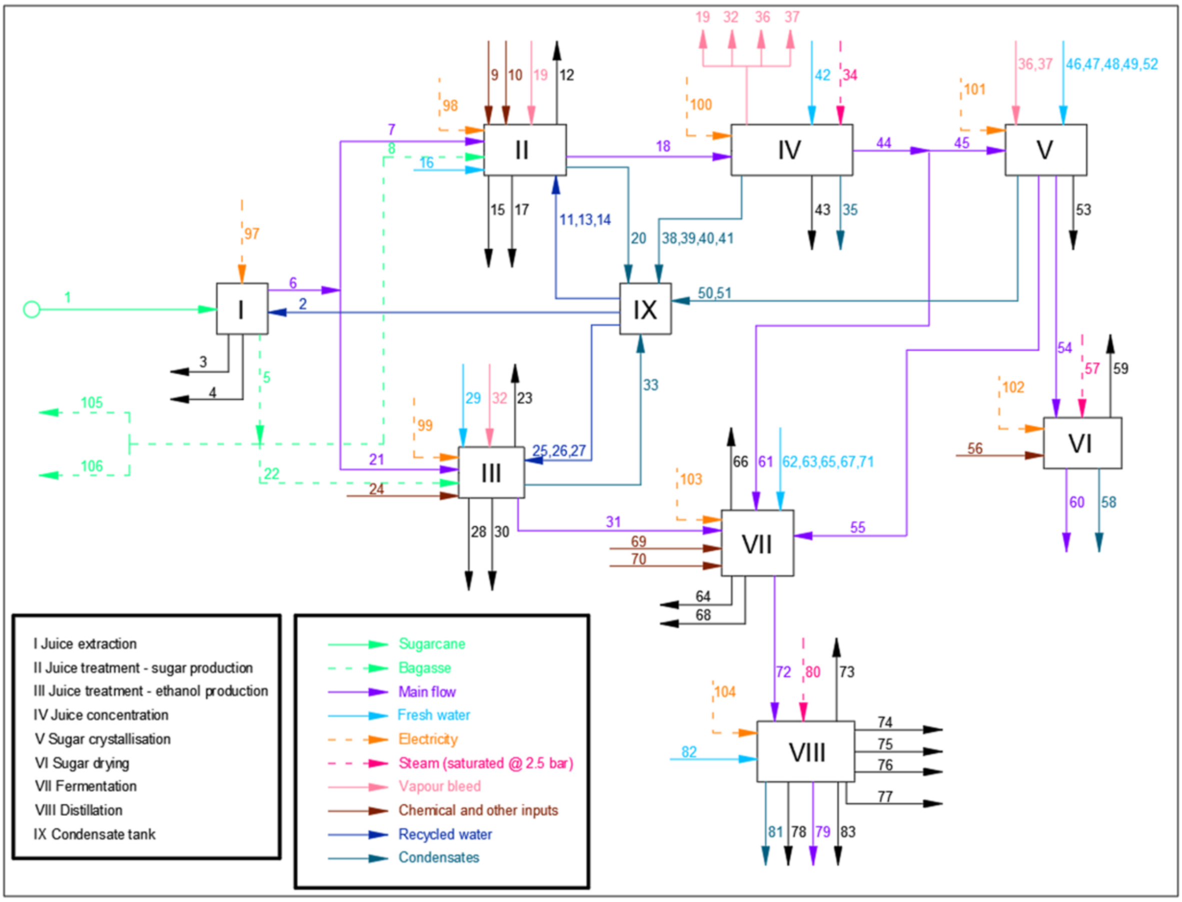

Fig. A.1. Flow sheet of conventional production process.

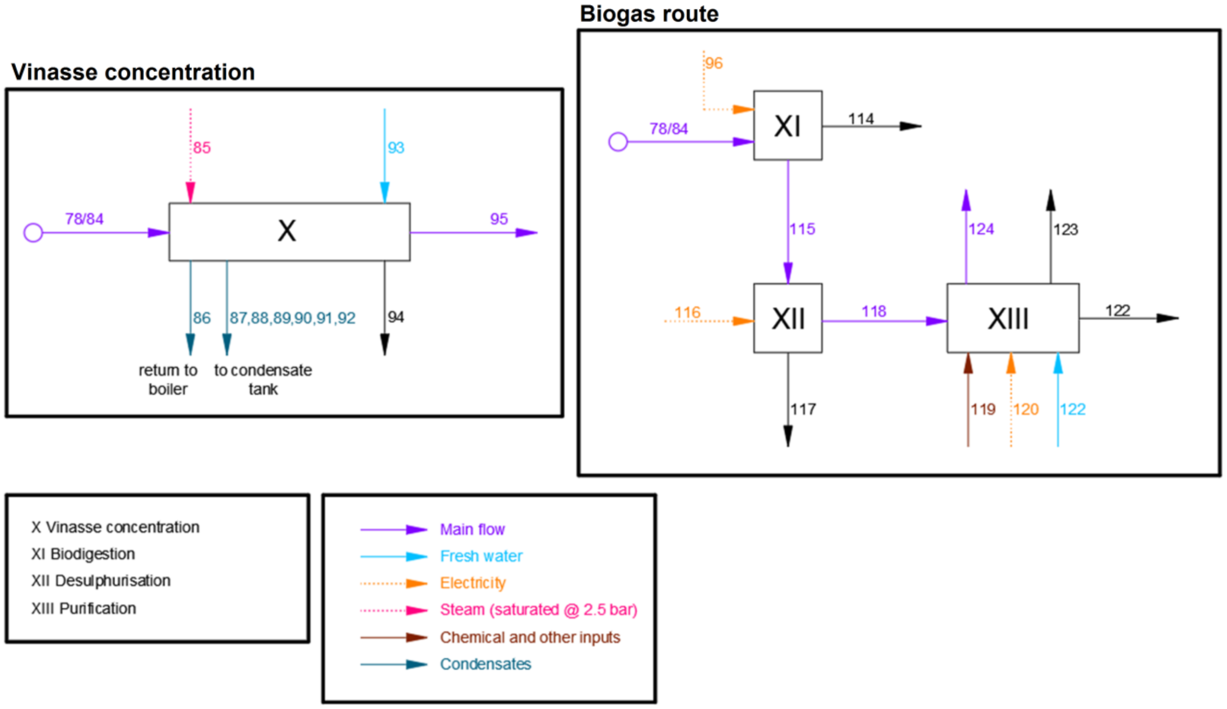

Fig. A.2. Flow sheet of concentration and biogas routes.

Appendix B

Table B1 presents the description of the process streams used in this study.

Description		$\dot{m}$ *(kg/s)*	*T* *(°C)*	*P* *(bar)*	*brix,* %	*ethanol,* %	*ex* *(kJ/kg)*
1	Sugarcane	138.9	25	1.013	19.14	–	5760
2	Imbibition water	41.67	50	1.013	–	–	54.1
3	Removed impurities	1.727	25	1.013	–	–	–
4	Loss of sucrose	0.3991	32.01	1.013	–	–	–
5	Bagasse	37.77	32.01	1.013	1.66	–	10,055
6	Raw juice	140.7	32.01	1.013	15.41	–	2,742
7	Raw juice – sugar production	98.46	32.01	1.013	15.41	–	2,742
8	Bagasse for filters – sugar production	0.4861	32.01	1.013	1.66	–	10,055
9	SO_2 for sulphitation – sugar production	0.08333	25	1.013	–	–	4,892
10	CaO for liming – sugar production	0.1258	25	1.013	–	–	1,965
11	Water for $Ca(OH)_2$ preparing –sugar production	1.963	25	1.013	–	–	49.96
12	Vapour from flash – sugar production	1.275	99.02	0.97	–	–	532.4
13	Water for polymer dilution – sugar production	1.458	25	1.013	–	–	49.96
14	Water for filter – sugar production	2.917	25	1.013	–	–	49.96
15	Filter cake – sugar production	3.966	87.55	1.013	–	–	–
16	Water for barometric condenser – sugar production	17.66	30	1.013	–	–	50.13
17	Outlet of barometric condenser – sugar production	18.28	50.38	0.3	–	–	54.15
18	Clarified juice – concentration	99.63	98.11	1.013	14.76	–	2,658
19	*Vegetal Vapour* – sugar production	14.06	115.3	1.69	–	–	613.2
20	Condensate of *vegetal vapour* – sugar production	14.06	115	1.69	–	–	97.76
21	Raw juice – ethanol production	42.2	32.01	1.013	15.41	–	2,742
22	Bagasse for filters – ethanol production	0.2083	32.01	1.013	1.66	–	10,055
23	Vapour from flash – ethanol production	0.5363	99.02	0.97	–	–	532.4
24	CaO for liming – ethanol production	0.06944	25	1.013	–	–	1,965
25	Water for $Ca(OH)_2$ preparing – ethanol production	1.083	25	1.013	–	–	49.96
26	Water for polymer dilution – ethanol production	0.625	25	1.013	–	–	49.96
27	Water for filter – ethanol production	1.25	25	1.013	–	–	49.96
28	Filter cake – ethanol production	1.681	86.11	1.013	–	–	–
29	Water for barometric condenser – ethanol production	6.957	30	1.013	–	–	50.13
30	Outlet of barometric condenser – ethanol production	7.201	50.38	0.3	–	–	54.15
31	Clarified juice – must preparation	42.97	96.45	1.013	14.67	–	2,641
32	*Vegetal vapour* – ethanol production	5.852	115.3	1.69	–	–	613.2
33	Condensate of *vegetal vapour* – ethanol production	5.852	115	1.69	–	–	97.76
34	Exhaust steam – juice evaporation system	44.18	127.4	2.5	–	–	668.4
35	Condensate of exhaust steam – juice evaporation system	42.42	127.4	2.5	–	–	110.7
36	*Vegetal vapour* for pan 1– crystallisation	11.39	115.3	1.69	–	–	613.2
37	*Vegetal vapour for pan 2* – crystallisation	1.825	115.3	1.69	–	–	613.2
38	Condensate of *vegetal vapour* – first effect	7.332	115	1.69	–	–	97.76
39	Condensate of *vegetal vapour* – second effect	8.035	107.3	1.307	–	–	90.41
40	Condensate of *vegetal vapour* – third effect	8.737	97.63	0.93	–	–	81.94
41	Condensate of *vegetal vapour* – fourth effect	9.495	83.27	0.54	–	–	71.04
42	Water for barometric condenser – juice concentration	298.9	30	1.013	–	–	50.13
43	Outlet of barometric condenser – juice concentration	306.2	50.18	0.16	–	–	54.08
44	Syrup	22.62	55.5	0.16	65	–	11,422
45	Syrup for crystallisation	21.5	55.5	0.16	65	–	11,422
46	Water for centrifuge 1 – crystallisation	1.748	107.4	6	–	–	90.94
47	Water for pan 2 – crystallisation	0.3942	107.4	6	–	–	90.94
48	Water for centrifuge 2 – crystallisation	1.291	107.4	6	–	–	90.94
49	Water for molasses dilution – crystallisation	0.653	107.4	6	–	–	90.94
50	Condensate of *vegetal vapour* from pan 1	11.39	115	1.69	–	–	97.76
51	Condensate of *vegetal vapour* from pan 2	1.825	115	1.69	–	–	97.76
52	Water for barometric condenser – crystallisation	283.3	30	1.013	–	–	50.13
53	Outlet of barometric condenser – crystallisation	293.2	50.39	0.16	–	–	54.15
54	Wet sugar	9.498	69.63	0.16	99.9	–	17,596
55	Molasses	6.147	57.68	0.16	73	–	12,824
56	Cold air – sugar drying	4.54	25	1.013	–	–	–
57	Exhaust steam – sugar drying	0.1566	127.4	2.5	–	–	668.4
58	Condensate of exhaust steam – sugar drying	0.1566	127.4	2.5	–	–	110.7

59	Wet air	4.54	25	1.013	–	–	–
60	Dry sugar	9.498	25	1.013	99.9	–	17,537
61	Syrup for must preparation	1.26	55.5	0.16	65	–	11,422
62	Water for must dilution	2.109	25	1.013	–	–	49.96
63	Cooling water for must	521	25	1.013	–	–	49.96
64	Outlet of cooling water	521	30	1.013	–	–	50.13
65	Water for gas separation – fermentation	1.888	25	1.013	–	–	49.96
66	Separated CO_2	4.433	30.8	1.013	–	–	–
67	Water for centrifuge – fermentation	13.28	25	1.013	–	–	49.96
68	Yeast purge	0.6988	29.78	1.013	–	–	–
69	Nutrient for yeast (NH_3)	0.01557	25	1.013	–	–	19,841
70	H_2SO_4 for pH regulation	0.0006944	25	1.013	–	–	1,666
71	Water for yeast treatment	11.02	25	1.013	–	–	49.96
72	Wine	73.43	29.86	1.013	–	6.153	2,183
73	Gases separated – distillation	0.08617	35	1.338	–	9.028	–
74	Second-grade ethanol	0.09807	35	1.338	–	88.64	26,135
75	Fusel oil 4	0.008333	90.32	1.16	–	25.2	–
76	Fusel oil 26	0.02444	82.28	1.16	–	83.3	–
77	Phlegmasse	5.67	103.6	1.16	–	0.219	169.9
78	Vinasse (as diluted solution)	62.88	74.86	1.393	4.39	0.02049	415.7
79	Hydrated ethanol	4.667	35	1.16	–	93.77	27,641
80	Exhaust steam – distillation	15.31	127.4	2.5	–	–	668.4
81	Condensate of exhaust steam – distillation	15.31	127.4	2.5	–	–	110.7
82	Cooling water – distillation	931.5	25	1.013	–	–	49.96
83	Outlet of cooling water	931.5	30	1.013	–	–	50.13
84	Vinasse (as solid fuel)	62.88	74.86	1.393	4.39	0.02049	651.4
85	Exhaust steam – vinasse concentration	13.44	127.4	2.5	–	–	668.4
86	Condensate of exhaust steam – vinasse concentration	13.44	127.4	2.5	–	–	110.7
87	Condensate of *vegetal vapour* – 1st effect of vinasse concentration system	7.399	122.3	2.139	–	–	105.2
88	Condensate of *vegetal vapour* – 2nd effect of vinasse concentration system	7.825	116.7	1.788	–	–	99.43
89	Condensate of *vegetal vapour* – 3rd effect of vinasse concentration system	8.203	110.3	1.449	–	–	93.19
90	Condensate of *vegetal vapour* – 4th effect of vinasse concentration system	8.527	102.8	1.12	–	–	86.35
91	Condensate of *vegetal vapour* – 5th effect of vinasse concentration system	8.788	93.58	0.802	–	–	78.66
92	Condensate of *vegetal vapour* – 6th effect of vinasse concentration system	8.967	81.12	0.496	–	–	69.58
93	Water for barometric condenser – vinasse concentration	252.3	30	1.013	–	–	50.13
94	Outlet of barometric condenser – vinasse concentration	261.4	50.38	0.3	–	–	54.15
95	Concentrated vinasse	4.15	60.07	0.2	65	–	8,935
96	Electricity for vinasse biodigestion	–	–	–	–	–	9.583*
97	Electricity for juice extraction	–	–	–	–	–	9200*
98	Electricity for juice treatment – sugar production	–	–	–	–	–	450*
99	Electricity for juice treatment – ethanol production	–	–	–	–	–	450*
100	Electricity for juice concentration	–	–	–	–	–	900*
101	Electricity for sugar crystallisation	–	–	–	–	–	1800*
102	Electricity for sugar drying	–	–	–	–	–	150*
103	Electricity for fermentation	–	–	–	–	–	600*
104	Electricity for distillation	–	–	–	–	–	450*
105	Bagasse for self-consumption	1.889	32.01	1.013	1.66	–	10,055
106	Bagasse for boiler	35.19	32.01	1.013	1.66	–	10,055
107	Bagasse surplus	0	32.01	1.013	1.66	–	10,055
108	Steam generated in boiler	A	520	65	–	–	1,462
109	Process steam	B	127.4	2.5	–	–	668.4
110	Condensates of process steam (return to boiler)	C	102	2.09	–	–	85.75
111	Make-up water – cogeneration system	D	25	2.09	–	–	50.07
112	Electricity for pump 1 – cogeneration system	–	–	–	–	–	E*
113	Electricity for pump 2 – cogeneration system	–	–	–	–	–	F*
114	Biodigested vinasse	62.37	30	1.013	–	–	130.3
115	Biogas	0.5138	30	1.013	–	–	18,499
116	Electricity for desulphurisation	–	–	–	–	–	56.62*
117	Effluent from desulphurisation	0.0767	35	1.1	–	–	–
118	Clean biogas	0.4371	35	1.1	–	–	19,795
119	Air – biogas purification	1.46	25	1.01	–	–	–

120	Electricity for purification	–	–	–	–	–	344.7[*]
121	Make-up water – biogas purification	2.404	20	1.1	–	–	50.14
122	Water purge	2.404	15	1.1	–	–	50.68
123	Exhaust stream – biogas purification	1.723	15	1.1	–	–	64.59
124	Biomethane	0.1748	15	10	–	–	49,116

[*] Total exergy; **A**: 76.69 kg/s for Case i, 85.91 kg/s for Case ii, 78.93 kg/s for Case iii, 76.69 kg/s for Case iv; **B**: 59.65 kg/s for Case i, 73.09 kg/s for Case ii, 59.65 kg/s for Case iii, 59.65 kg/s for Case iv; **C**: 57.26 kg/s for Case i, 70.17 kg/s for Case ii, 57.26 kg/s for Case iii, 57.26 kg/s for Case iv; **D**: 2.379 kg/s for Case i, 2.924 kg/s for Case ii, 2.386 kg/s for Case iii, 2.379 kg/s for Case iv; **E**: 2.619 kW for Case i, 1.848 kW for Case ii, 2.998 kW for Case iii, 2.619 kW for Case iv; **F**: 640.2 kW for Case i, 717.9 kW for Case ii, 659.6 kW for Case iii, 640.2 kW for Case iv