Exergy cost assessment of Very High Gravity (VHG) Fermentation in the sugarcane industry

Milagros Cecilia Palacios-Bereche[a], Reynaldo Palacios-Bereche[b], Antonio Garrido Gallego[c], Luis M. Serra[d], Miguel A. Lozano[e] and Silvia Azucena Nebra[f]

[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, SP., Brazil, reynaldo.palacios@ufabc.edu.br,
[c] Federal University of ABC, Santo André, SP., Brazil, a.gallego@ufabc.edu.br,
[d] GITSE-I3A, Department of Mechanical Engineering, Universidad de Zaragoza, Spain, serra@unizar.es,
[e] GITSE-I3A, Department of Mechanical Engineering, Universidad de Zaragoza, Spain, miguel.lozano@unizar.es,
[f] Federal University of ABC, Santo André, S.P., Brazil/ University of Campinas, Campinas, S. P., Brazil, silvia.nebra@ufabc.edu.br

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, whose disposition represents a problem for the industry because of its high production rate, which ranges from 10 to 15 litres of vinasse per litre of ethanol produced. In this way, the evaluation of technologies that could reduce the vinasse volume—either reducing its production during ethanol production process or its volume once already produced—is advantageous to the process and its sustainability, seeing as a lower amount of vinasse would allow a better and appropriate disposal of this effluent. This way, this work addresses the vinasse problem by a preliminary exergy cost analysis of two different technologies for vinasse volume reduction and a Base Case for comparison purposes; being the analysed cases: i) a Base Case (conventional production process), ii) the introduction of the VHG (Very High Gravity) fermentation with the use of ejectors as complementary refrigeration system, aiming at utilising a more concentrated most during fermentation to produce a wine with a higher ethanol content, thus reducing the amount of vinasse produced in the distillation step. The analysis aims at comparing the unitary exergy costs of the main products and by-products of the different alternatives, and identifying the processes with the highest irreversibilities associated, which resulted in the fermentation with distillation volume control, with values of 37.1% and 41%, for the conventional and VHG cases, respectively.

Keywords:

Vinasse; VHG fermentation; Exergy cost.

1. Introduction

The sugar and ethanol industry from sugarcane has an important role in the Brazilian agribusiness, being the ethanol demand quite significant in the Brazilian market [1], [2]; resulting in a desire of a more efficient ethanol production. Thus, seeing as the fermentation is a crucial step in ethanol production, where it is formed through a biochemical reaction lead by yeast, a more efficient fermentation process will lead, therefore, to an improved ethanol production. In this way, maintaining an adequate fermentation temperature is essential to favour ethanol production, as one of the most important parameters in this process. That being so, a low-temperature fermentation has been proved to result in higher ethanol yields since a more concentrated substrate can be used [3].

By lowering the fermentation temperature, a higher ethanol concentration in the wine is obtained, since the inhibition of organic acids and ethanol is reduced, and the flocculation and bacterial contamination is better controlled. In addition, a fermentation temperature lower than the conventional one, also allows the use of a high substrate concentration in the must, leading, in turn, to a Very High Gravity (VHG) fermentation, which is an emerging and versatile technology that offers great savings in process water and energy requirements during the distillation and fermentation steps, by reducing the size of distillation columns and decreasing the power consumption of yeast centrifugation, respectively, because of the higher concentrations of sugar in the

 https://doi.org/10.52202/069564-0153

substrate, which leads to a higher final ethanol concentration in the medium. In addition, seeing as the ethanol content is higher in the wine, the amount of water and impurities is reduced, thus producing a lower amount of vinasse [3]–[5].

That being said, a cooling system is necessary to reach and maintain an adequate temperature. Since the fermentation process is an exothermic reaction, cooling towers have been conventionally used to control and maintain a fermentation temperature of around 34°C. Nevertheless, sometimes, the cooling water provided by cooling towers cannot achieve a temperature low enough to reach an appropriate fermentation temperature range because of adverse environmental conditions. In this way, alternative refrigeration systems are necessary when a fermentation with high sugar concentration in the substrate is applied.In this way, this work assesses the VHG fermentation against the conventional production process through a preliminary exergy cost analysis. In order to mantain the fermentation temperature in appropriate levels that make viable the VHG fermentation, a complementary refrigeration system based on ejectors was assumed for this case. Regarding the exergy cost assessment, this is a tool that aims at identifying 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 optimisation studies [6]. Although the application of ejectors in cooling systems, as well as the assessment of the VHG fermentation, have already been regarded in the literature separately, there is a lack of studies either combining these technologies or evaluating the impacts of the VHG fermentation in the production and cogeneration systems; besides, studies evaluating these systems from exergy and exergy cost approaches are yet to be found.

2. Processes description and evaluated cases

2.1. Case i: Conventional fermentation – Base Case

A conventional fermentation was considered as a “Base Case,” according to Figure 1.

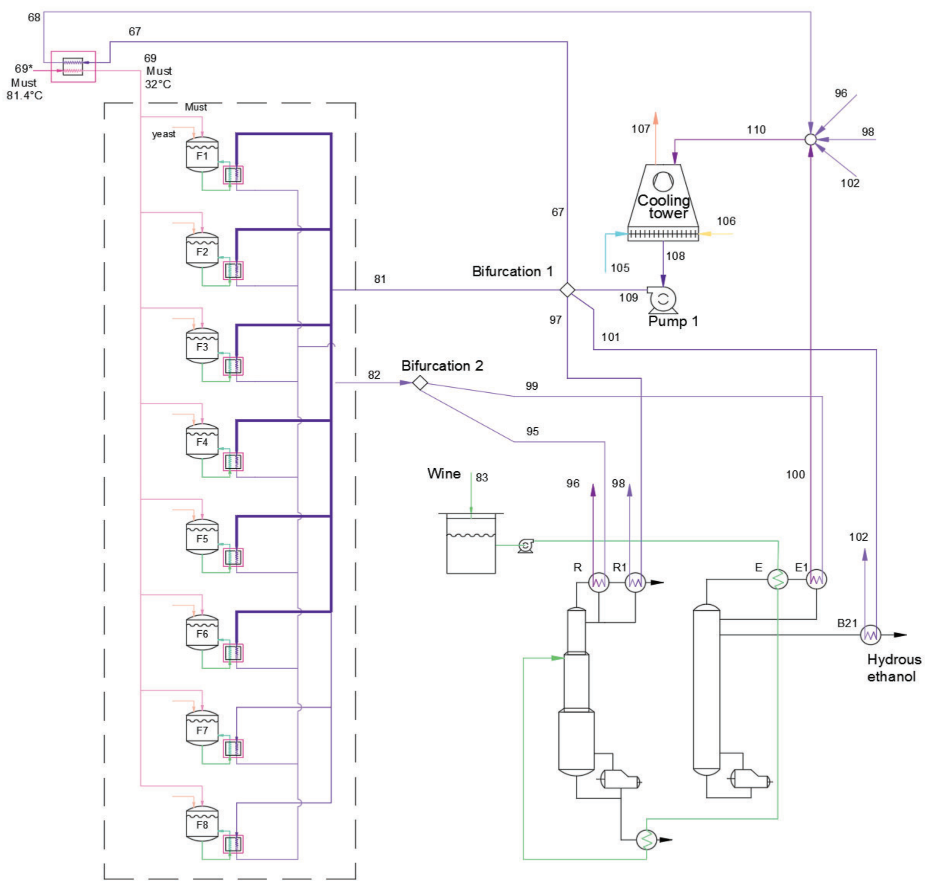

Figure. 1. Conventional fermentation operating with 8 fermentation vats, using water from the cooling tower as the only cold utility.

https://doi.org/10.52202/069564-0153

A cooling tower was adopted to supply water to meet the requirements of cold utilities in the plant, including removing the heat from the fermentation exothermic reaction, since this is a cooling system that is usually adopted in the industry. In this system, cooling water is used in the heat exchangers of fermentation vats, must cooling, and distillation system. A fermentation system operation with 8 vats was assumed, where 6 vats are being cooled simultaneously.

2.2. Case ii: VHG fermentation using an ejector system

Refrigeration systems based on the use of ejectors are an attractive alternative to compression vapour and absorption refrigeration systems because of their mechanical simplicity, which represents an easy maintenance and operation. Notwithstanding, some drawbacks of these systems include an increase in steam and energy consumption, as well as the high vacuum required in the evaporator [3]. In this study, a two-stage ejector system was chosen to aid the cooling tower, according to Figure 2. First, the chilled water (14°C) from the ejector system is used to refrigerate the fermentation vats and cool the must down to 28°C. Then, the cooling water that returns from the fermentation vats and must heat exchangers (stream 122) is mixed with the return water from the cooling tower (stream 121); this mixture is sent to a first flash tank at 20°C, where the first ejector is driven using steam at 9 bar. Next, the cooled water in this first stage is sent to a second flash tank at 14°C, whose low temperature is maintained by the vacuum generated by the second ejector. The chilled water is then sent to a buffer tank for storage before use. Afterwards, the steam at the ejectors' outlet (streams 119 and 120), at an intermediate pressure, is condensed in a barometric condenser. Finally, a fraction of this condensed water (stream 113) is sent to the cogeneration system of the mill, while the rest is cooled in the cooling tower. The fermentation operation assumed 8 vats, where 3 vats are cooled with chilled water and 3 are cooled with cold water from the cooling tower, simultaneously.

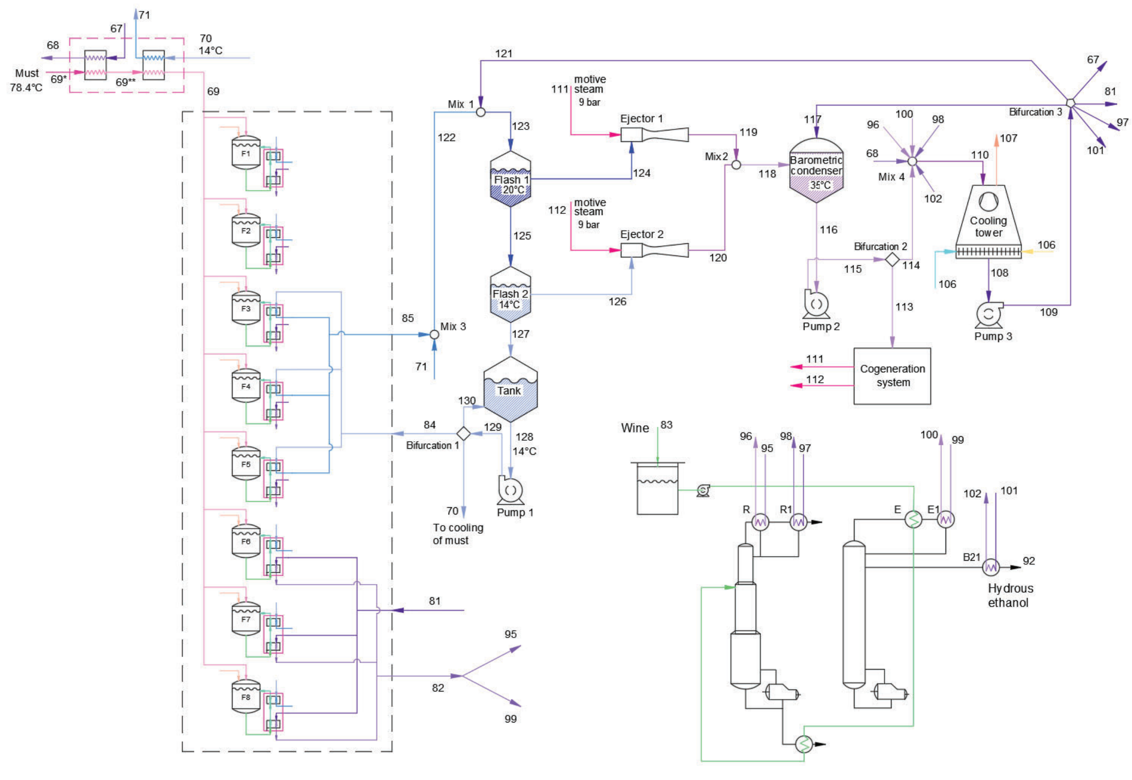

Figure. 2. Low-temperature fermentation operating with 8 fermentation vats, using cold and chilled water from the cooling tower and ejector system, respectively, as cold utilities.

2.3. Cogeneration system

The cogeneration system adopted was based on a Rankine cycle, considering back-pressure steam turbines, where the steam generation depends on the steam consumption of the overall production process. Figure 3 (a) presents a scheme of the cogeneration system for the conventional fermentation (Case i), while Figure 3 (b) shows a scheme of the cogeneration system when the VHG fermentation is considered (Case ii), where a steam bleed at 9 bar is needed to operate the ejector cooling system. The boiler pressure and temperature were

 https://doi.org/10.52202/069564-0153

adopted at 65 bar and 520°C, according to [7], considering a boiler efficiency of 85%, according to [8], and turbine and pump efficiencies of 80%, as stated in [9].

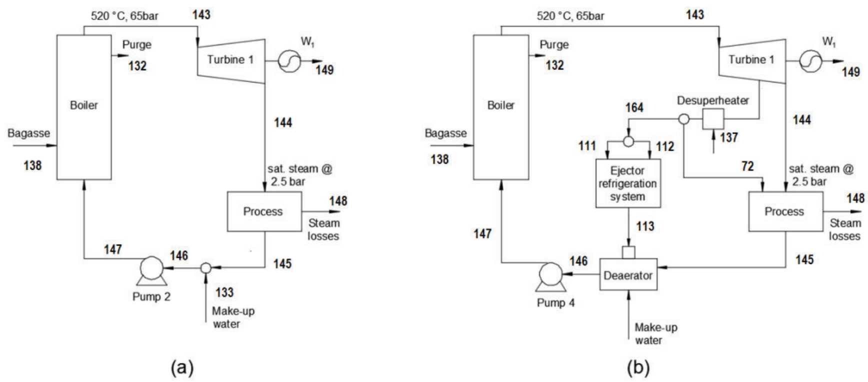

Figure. 3. Cogeneration system for (a) Case i and (b) Case ii.

3. Methodology

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

- Modelling and simulation of the conventional production process (Base Case), VHG fermentation integrated thereof, and cogeneration system;
- exergy analysis;
- exergy cost assessment.

3.1. Modelling and simulation

Two cases of a conventional ethanol and sugar production process were simulated using the software Aspen Plus v9 [10], according to [11], considering a sugar concentration of 16% and 35% (m/m) in the must for the conventional and VHG fermentation cases, respectively. Table 1 shows the main data assumed in the aforementioned simulation.

Table 1. Main parameters for the simulation of the ethanol and sugar production process.

Parameter	Value
Sugarcane processing rate, t/h	500
Bagasse production in mills, kg/t cane	272
Bagasse for filters, kg/t cane	5
Bagasse for self-consumption, %	5
Sugar production, kg/t cane	68.4
Hydrous ethanol, m^3/h	21.1
Vinasse production, m^3/h	247.8
Electricity consumption in conventional process, kWh/t cane	28
Steam consumption in conventional process, kg/t cane	437.6

Source: Palacios-Bereche et al. [11]

3.2. Kinetic modelling for conventional and VHG fermentation

First, the modelling of both, the conventional and VHG fermentation, was performed using the software Scilab. The kinetic model from [12] was chosen for the conventional fermentation, seeing that the best results were obtained since the model used a high cellular density and a cell recycle that were closer to the actual concentration used in the commercial process, which resulted in a better convergence than other models that used a low-cell concentration, and a more realistic modelling [12]–[17]. On the other hand, the kinetic model from [18] was used for the VHG fermentation, as this model was validated for very-high-gravity (VHG) fermentation conditions.

Then, an analysis of the heat exchanger of the fermentation vat was performed using the effectiveness approach, according to [19]. This method allows the calculation of the outlet temperatures of the heat exchanger for off-design conditions keeping constant the parameters R (relation of heat capacities) and P (effectiveness). In the conventional fermentation, these parameters (R and P) were calculated assuming the data from [20]. The temperature of the cooled wine that returns to the fermenter (T_{16}) is used as feedback for the energy balance in the fermentation vat. Finally, the cold water mass flow is calculated through an energy balance in the heat exchanger. The same approach was assumed when the chilled water from the ejector system was used in the VHG fermentation case.

Finally, the ejector was modelled following the procedure presented in [21], due to its simplicity and the possibility of performing a thermodynamic analysis of the ejector system, without dimensioning the equipment. It is highlighted some design parameters that were considered for the simulations: a nozzle efficiency of 71.2% and 73.5%, a compression efficiency in the diffuser of 67.8% and 71.3%, and an efficiency of momentum transfer of 60.0% and 63.8%, all of them for ejectors 1 and 2, respectively. These values were used so that the steam consumption results obtained were similar to real systems that operate at the same thermal capacity.

Table 2 presents the fermentation parameters and initial conditions assumed for the fermentation process in the conventional and VHG fermentation processes.

Table 2. Main parameters for the fermentation modelling.

Parameter	Case i (Conventional)	Case ii (VHG fermentation)
Must feed		
Substrate feed volume rate, $\dot{F}$ [m^3/h]	67.1[*(a)]	42.0[*(a)]
Feed substrate concentration, S_in [kg/m^3]	169.7[(a)]	407.2[(b)]
Inlet must temperature, T_{18} [°C]	32.0[(a)]	28.0[(a)]
Specific heat capacity, cp_{in} [kJ/kg-K]	3.8[(c)]	3.34[(c)]
Density, ρ_{in} [kg/m^3]	1060.4[(c)]	1151.6[(c)]
Fermentation parameters		
Fermentation time, t [h]	8	15[(b)]
Feed time, t_{feed} [h]	4	5
Initial conditions		
Initial substrate concentration, S_0 [kg/m^3]	0	0
Initial ethanol concentration, P_0, [kg/m^3]	40[(b)]	26.96[(b)]
Initial cell concentration, X_0 [kg/m^3]	120[(b)]	52.08[(b)]
Initial temperature, T15_0 [°C]	32.0[(d)]	28.0[(d)]
Cooling		
Water temperature from the cooling tower, T_{cw} [°C]	28.0	28.0
Volume flow rate of fermenter recycle, V_{15} [m^3/h]	500[**(b)]	308[**(b)]
Water temperature from ejector system T_8, [°C]	-	14[(d)]
Operating time of ejector[***], [h]		7.5

[(a)] From simulation in Aspen Plus v9; [(b)] [17]; [(c)] Calculated from [22]; [(d)] [23]
[*] Corresponding to a 50/50 sugarcane-processing plant that uses 50% of the total recoverable sugars (TRS) to produce sugar and the other 50% to produce ethanol, which is made from a mixture of cane juice, syrup, and molasses.
[**]1 hour of feeding
[***] The ejector was set to start operating two hours and a half after finishing the feeding time (7.5 h) until the end of the fermentation process.

3.3. Exergy calculation

The exergy of each stream of the evaluated processes was calculated according to previous studies [24], [25]. A reference level was chosen at 25°C and 1.01325 bar, according to [26]. The total thermal exergy (ex_{tot}) was calculated as the sum of the physical (ex_{phy}) and chemical (ex_{ch}) exergies [26]:

$$ex_{tot} = ex_{phy} + ex_{ch} . \tag{1}$$

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

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

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 [26]:

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

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

https://doi.org/10.52202/069564-0153

according to the guidelines presented in [27]. On the other hand, for ethanol-containing streams, the guidelines in [28] were followed.

3.4. 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 [6]. 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 [6]. The Theory of Exergetic Cost [29] 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:

$$\sum \dot{B}_{in} = \sum \dot{B}_{out}, \tag{4}$$

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

According to [29], the exergetic cost of a flow ($\dot{B}$) is defined as the amount of exergy required to produce said flow (5):

$$\dot{B}_i = k_i \cdot \dot{E}x_i, \tag{5}$$

where the exergetic cost of an *i* stream is determined by its unit exergetic cost (k_i) and its total exergy $\left(\dot{E}x_i\right)$. 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 [29], 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).

$$k_{external input} = 1. \tag{6}$$

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

$$k_{by-product} = k_{input}. \tag{7}$$

As was the case of bagasse, molasses, phlegmasse, and vinasse, were the following were considered:

$$k_{bagasse} = k_{sugarcane}, \tag{7.1}$$

$$k_{molasses} = k_{syrup}, \tag{7.2}$$

$$k_{vinasse} = k_{phlegmasse} = k_{must}. \tag{7.3}$$

- 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).

$$k_{product1} = k_{product2} = \ldots = k_{productn}. \tag{8}$$

As in the case of second-grade ethanol and fusel oils, that were considered co-products and assigned an unit exergy cost equal to that of the hydrated ethanol

- 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.

$$k_{live\ steam} = k_{process steam} = k_{condensate} = k_{vapour bleeds}. \tag{9}$$

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

In Table 3, the main results of the evaluated processes are presented, from which it can be highlighted the significant reduction of 60% in vinasse production when the VHG fermentation was considered, which can significantly reduce transport and disposal costs related to this effluent. In addition, this technology also allowed a reduction in the effective water withdrawal of 72%, which would lead to environmental and economic advantages. Still, the use of the VHG fermentation required an increased steam consumption at 2.5 bar, although not significant (0.8%), which can be explained due to the increased consumption during the concentration step, as more raw juice needed to be concentrated; in this way, even though there was a steam consumption was lower in the distillation stage, it could not compensate the juice concentration steam demand; moreover, there is an additional steam consumption at 9 bar for thermal juice sterilisation, a necessary step in the VHG fermentation, and for the ejector system (motive steam). Regarding the surplus electricity, an increase of 6.8% was observed in the VHG case, in comparison to the Conventional case, due to the higher steam consumption in the first one (the electricity produced in backpressure steam turbines is directly proportional to the flow of steam being expanded). Thus, there is an increase in fuel consumption in the boiler, which is reflected in a reduction of 52.6% in surplus bagasse in the VHG case, when compared to the Conventional case.

Table 3. Main results of evaluated processes

Parameter	Case i Conventional	Case ii VHG fermentation
Sugarcane, processed, t/h	500	500
Raw juice for sugar production, %	70	91.4
Sugar production, kg/t cane	68	68
Must for fermentation, kg/t cane	427.2	195.5
Must for fermentation, Brix	19.42	42.47
Ethanol content in wine, % (wt.)	6.15	12.37
Hydrated ethanol production[a], L/t cane	43.8	43.8
Steam consumption in process at 2.5 bar, kg/t cane	435.6	439.3
Steam consumption in process at 9 bar, kg/t cane	0	18.8
Vinasse production, kg/t cana	511.6	203.0
Vinasse production, L/L hydrated ethanol	12.8	5.1
Effective water collection, kg/t cane	418.7	116.2
Surplus electricity in cogeneration system, kWh/t cane	47.2	50.4
Surplus bagasse, kg/t cane	25.1	11.9

[a]At 35°C

Figure 4 shows the distribution and the connexion between the analysed subsystems in this study, for Cases I and II. In both cases, the fermentation and distillation processes were evaluated together, including the cold utility production system for these processes (cooling tower and chilled water) in the exergy and exergy cost assessments.

Table 4 presents the irreversibilities (kWh/t cane) calculated through the exergy balance in each sub-system considered in the analysis. The boiler subsystem presented the highest irreversibility for both cases, accounting for 62% and 60% of the total irreversibility for the Conventional and VHG cases, respectively, mainly due to the high irreversibilities in the combustion process. In second place, the Fermentation + Distillation subsystem represents 14.1 and 16.4% for the Conventional and VHG cases, respectively, this can be explained due to of the biochemical reaction in the fermentation process and the significant steam consumption in distillation columns; moreover, the cooling towers and the cooling ejector system in the VHG case were incorporated into this control volume. Next, the Juice extraction subsystem amounts to 12 and 10.9% for the Conventional and VHG cases, respectively, in this sub-system there is a significant power consumption in the mills. The following subsystem is the Juice treatment for sugar, which accounts for 4.7 and 6.8% for the Conventional and VHG cases, respectively. The following subsystems present a low irreversibility in comparison to the total.

https://doi.org/10.52202/069564-0153

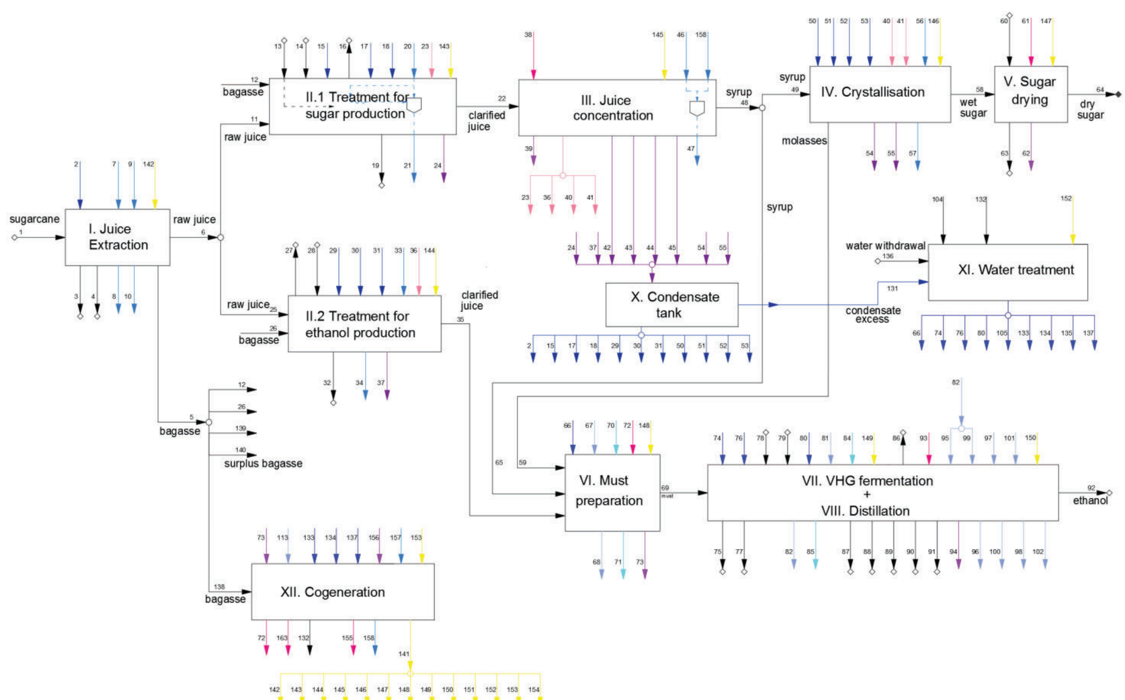

Figure. 5. Block diagram of the evaluated subsystems in the exergy and exergy cost assessments

Analysing the differences between the Conventional and VHG cases, an increase of 10.5% in total irreversibility can be observed, which can be explained by the additional requirements in the VHG case, such as the additional steam consumption in the must sterilisation in the fermentation process, and the steam demand in the cooling system based on ejectors. Moreover, there is a significant increase in the irreversibilities of the Juice treatment-sugar and Juice concentration subsystems, due to the larger amount of juice being concentrated and the layout assumed in this assessment.

Table 4. Irreversibilities in each sub-system for Conventional and VHG cases in kWh/t cane

Parameter	Case i Conventional (kWh/tcane)	Case ii VHG fermentation (kWh/tcane)
Juice extraction	91.4	91.4
Juice treatment - sugar	35.8	57.5
Juice treatment - ethanol	15.5	6.4
Juice concentration	14.9	19.5
Crystallisation	13.7	14.0
Sugar drying	1.6	1.6
Must preparation	4.1	2.9
Fermentation + Distillation	107.1	137.8
Water treatment	1.6	1.3
Boiler	472.4	504.8
Turbine	3.0	3.4
TOTAL	761.0	840.6

The results verification in the Base Case (Case i) can be done comparing results from other studies; however for VHG case verification of results was performed by calculating irreversibilities of the processes, in order to evaluate their thermodynamic feasibility from 2nd Law of Thermodynamic approach. In Figure 5, the irreversibilities are presented in percentage, without taking into account the boiler, aiming at a better visualisation of the contribution of each subsystem.

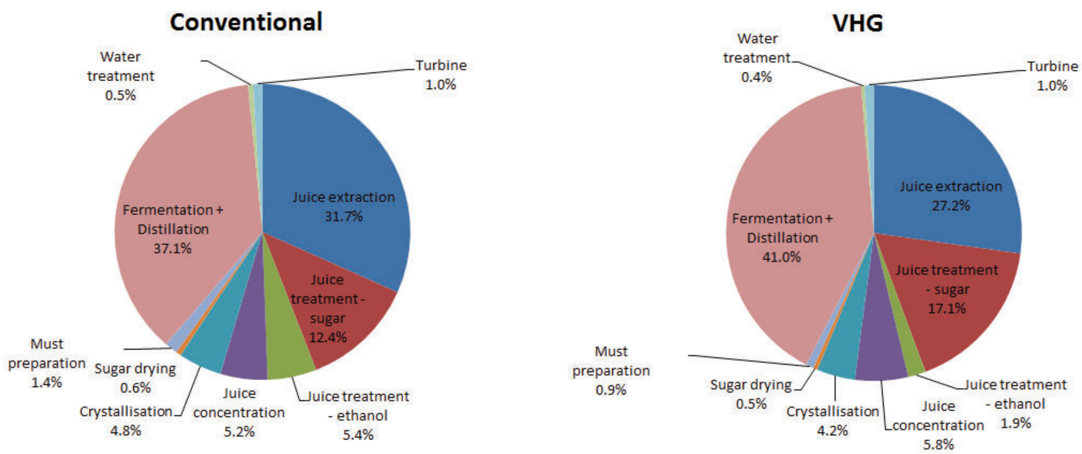

Figure. 5. Irreversibilities, in % without considering the boiler

Figure 6 presents the unitary exergy costs (kJ/kJ) of the main products and by-products of the analysed sub-systems for the Conventional and VHG fermentation cases. It can be observed that the highest unitary exergy cost corresponds to the hydrated ethanol because of the significant amount of processes required to produce it and the high irreversibilities associated to obtain this product; moreover, it can also be observed that the unitary exergy cost in the VHG case is higher than the Conventional case, mainly due to the higher costs of utilities produced in the cogeneration system, such as electricity and steam.

Regarding the other streams the difference between the Conventional and VHG cases is not significant (difference lower that 5.6%)

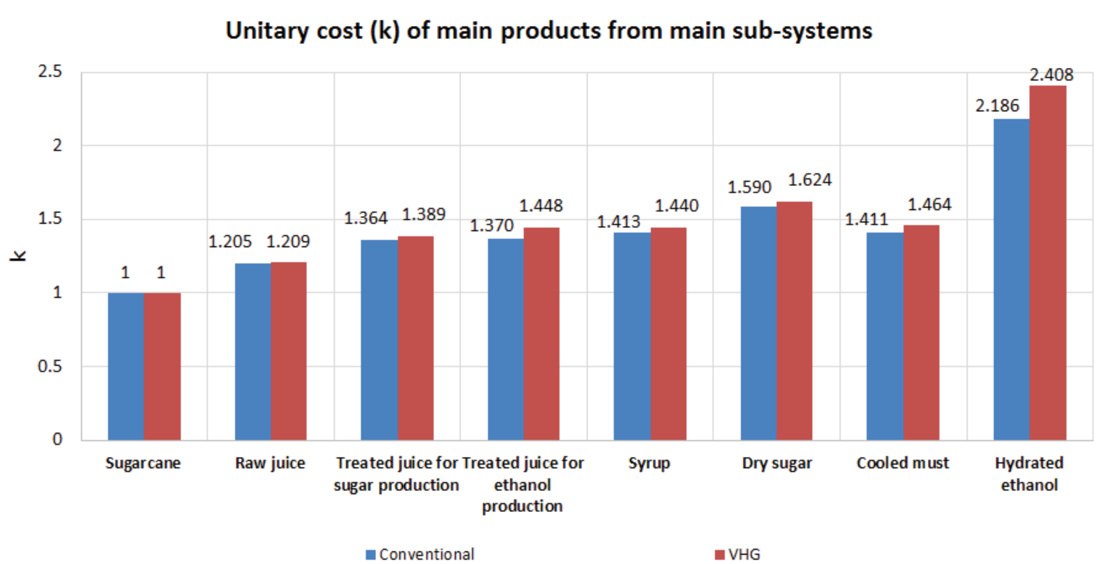

Figure. 6. Unitary exergy cost of main products and by-products for Conventional and VHG cases

Figure 7 presents the unitary exergy costs for the utilities produced in the process. It can be observed that the unitary exergy costs of steam, electricity and treated water are higher in the VHG case, in comparison to the Conventional case.

https://doi.org/10.52202/069564-0153

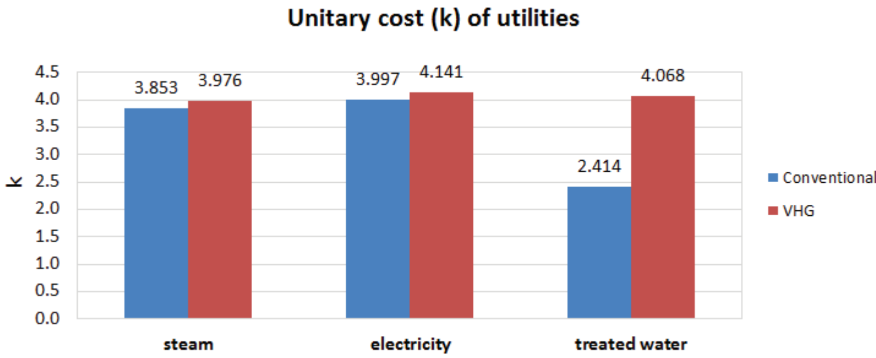

Figure. 7. Unitary exergy costs of the utilities produced in the process

Regarding the steam, its unitary exergy cost resulted higher in the VHG case, because the irreversibilities in the boiler, were the steam is produced, resulted higher as well, since more steam is necessary in this case, and more fuel is being burned. Regarding the electricity, the irreversibilities in the steam turbines are higher in the VHG case, as well; because more steam is being expanded through them; thus, the exergy cost to produce this electricity results higher as well. Concerning the treated water, although a smaller amount of water (33% of the total water use) is captured from the environment in the VHG case, in comparison to Conventional case (80% is captured in the conventional case), the exergy cost of the treated water was significantly higher (68.5%) in the VHG case. This can be explained by the fact that recycled and reused water streams come from the spray pond system and condensate tank, whose exergy cost was assumed equal to the steam ($k_{condensate}$=k_{steam}); in addition, the electricity consumption in the treated water system, where reverse osmosis membranes were assumed, had a specific energy consumption of 2.58 kWh/m^3 of water according to [30].

Conclusions

From the results, it is observed that the implementation of the VHG fermentation, using an ejector cooling system as auxiliary cooling utility, presents several advantages over the conventional production process, such as a significant reduction of the vinasse produced and a lower water withdrawal for the process, leading to economic and environmental advantages. Regarding the vinasse reduction, its volume could be further reduced when coupled with other technologies such as concentration by evaporation or incineration, or even membrane technologies; furthermore, the energy required in these technologies would be lesser than the energy needed when considering the volume and concentration of the vinasse produced in the conventional process. On the other hand, the exergy analysis revealed that the use of the VHG fermentation increased the irreversibilities of the overall process, besides impacting negatively in the cogeneration system, by increasing the unitary exergy costs of the utilities (steam and electricity), as well as increasing the unitary exergy cost of the hydrated ethanol. Moreover, even though there was an increase in surplus electricity, due to the higher consumption of steam, it leads to an also increased fuel (bagasse) consumption. Although the availability of bagasse surplus is desired when further processing of this residue is considered, such a production of second-generation ethanol, among others, further research and analyses are needed, in order to determine if the advantages here presented compensate this issue, such as economic and environmental assessments.

Acknowledgments

The authors wish to thank the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES) and the Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) (Process PQ 306303/2014-0 and PQ 309588/2019-7) for the researcher fellowship; and for the Research Project Grant (Process 407175/2018-0 and 429938/2018-7).

References

[1] X. Du and M. A. Carriquiry, ‘Flex-fuel vehicle adoption and dynamics of ethanol prices: Lessons from Brazil’, *Energy Policy*, vol. 59, pp. 507–512, 2013, doi: 10.1016/j.enpol.2013.04.008.

[2] A. L. Ferreira, F. P. de A. Prado, and J. J. da Silveira, ‘Flex cars and the alcohol price’, *Energy Econ.*, vol. 31, no. 3, pp. 382–394, 2009, doi: 10.1016/j.eneco.2009.01.007.

[3] M. O. S. Dias, R. Maciel Filho, and C. E. V. Rossell, ‘Efficient Cooling of Fermentation Vats in Ethanol Production – Part 1’, in *XXVI congress - International Society of Sugar Cane Technologists: ICC, Durban, SouthAfrica, 29 July - 2 August 2007; papers (English)*, 2007, vol. 26, no. December, pp. 1210–1217.

[4] L. A. B. Cortez, C. E. V. Rossell, R. A. Jordan, M. R. L. V. Leal, and E. E. S. Lora, ‘R&D needs in the industrial production of vinasse’, in *Sugarcane bioethanol: R&D for productivity and Sustainability*, 1st ed., L. A. B. Cortez, Ed. São Paulo: Blucher, 2010, pp. 619–636.

[5] P. Puligundla, D. Smogrovicova, V. S. R. Obulam, and S. Ko, ‘Very high gravity (VHG) ethanolic brewing and fermentation: a research update’, *J. Ind. Microbiol. Biotechnol.*, vol. 38, no. 9, pp. 1133–1144, Sep. 2011, doi: 10.1007/s10295-011-0999-3.

[6] G. Tsatsaronis, ‘Thermoeconomic analysis and optimization of energy systems’, *Prog. Energy Combust. Sci.*, vol. 19, no. 3, pp. 227–257, 1993, doi: 10.1016/0360-1285(93)90016-8.

[7] J. H. Sosa-Arnao, ‘Personal communication’, 2018.

[8] E. F. Cortes-Rodríguez, S. A. Nebra, and J. H. Sosa-Arnao, ‘Experimental efficiency analysis of sugarcane bagasse boilers based on the first law of thermodynamics’, *J. Brazilian Soc. Mech. Sci. Eng.*, vol. 39, no. 3, pp. 1033–1044, 2017, doi: 10.1007/s40430-016-0590-y.

[9] A. V. Ensinas, S. A. Nebra, M. A. Lozano, and L. M. Serra, ‘Analysis of process steam demand reduction and electricity generation in sugar and ethanol production from sugarcane’, *Energy Convers. Manag.*, vol. 48, no. 11, pp. 2978–2987, 2007, doi: 10.1016/j.enconman.2007.06.038.

[10] aspentech, ‘Aspen Plus’, 2018. https://www.aspentech.com/products/engineering/aspen-plus (accessed Sep. 23, 2018).

[11] M. C. Palacios-Bereche, R. Palacios-Bereche, and S. A. Nebra, ‘Comparison through energy, exergy and economic analyses of two alternatives for the energy exploitation of vinasse’, *Energy*, vol. 197, p. 117231, 2020, doi: 10.1016/j.energy.2020.117231.

[12] I. I. K. Veloso, K. C. S. Rodrigues, J. L. S. Sonego, A. J. G. Cruz, and A. C. Badino, ‘Fed-batch ethanol fermentation at low temperature as a way to obtain highly concentrated alcoholic wines: Modeling and optimization’, *Biochem. Eng. J.*, vol. 141, pp. 60–70, 2019, doi: 10.1016/j.bej.2018.10.005.

[13] M. V. A. Da Costa Filho, J. B. Monteiro, F. C. Magazoni, and S. Colle, ‘Modeling, simulation and analysis of ethanol fermentation process with control structure in industrial scale’, in *Proceedings of ECOS 2009 - 22nd International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems*, 2009, no. August 2009, pp. 1351–1360.

[14] D. I. P. Atala, ‘Fermentação alcoólica com alta densidade celular: Modelagem cinética, convalidação de parâmetros e otimização do processo’, Universidade Estadual de Campinas, 2000.

[15] G. C. Fonseca, C. B. B. Costa, and A. J. G. Cruz, ‘Comparing a dynamic fed-batch and a continuous steady-state simulation of ethanol fermentation in a distillery to a stoichiometric conversion simulation’, *Brazilian J. Chem. Eng.*, vol. 34, no. 4, pp. 1121–1131, 2017, doi: 10.1590/0104-6632.20170344s20160155.

[16] F. C. Magazoni, J. B. Monteiro, J. M. Cardemil, and S. Colle, ‘Cooling of Ethanol Fermentation Process Using Absorption Chillers’, *Int. J. Thermodyn.*, vol. 13, no. 3, pp. 111–118, 2010, doi: 10.5541/IJOT.1034000167.

[17] C. E. V. Rossell, ‘Personal communication’, 2020.

[18] E. Ccopa Rivera *et al.*, ‘Effect of temperature on sugarcane ethanol fermentation: Kinetic modeling and validation under very-high-gravity fermentation conditions’, *Biochem. Eng. J.*, vol. 119, pp. 42–51, 2017, doi: 10.1016/j.bej.2016.12.002.

[19] N. Kayansayan, ‘Thermal behavior of heat exchangers in off-design conditions’, *Heat Recover. Syst. CHP*, vol. 9, no. 3, pp. 265–273, 1989, doi: 10.1016/0890-4332(89)90010-0.

[20] C. K. Yamakawa, ‘Avaliação da fermentação alcoólica com reciclo de células de hidrolisado celulósico de bagaço de cana-de-açúcar em unidade integrada e autônoma’, Universidade Estadual de Campinas, 2016.

[21] D. Q. Kern, *Procesos de Transferencia De Calor*, 31st ed. México, D.F.: McGraw Hill Book Company, 1999.

[22] S. A. Nebra and M. I. Fernández-Parra, ‘The Exergy of Sucrose-Water Solutions: Proposal of a Calculation Method’, in *Proceedings of ECOS 2005 - The 18th International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems*, 2005, pp. 385–392.

[23] C. E. V. Rossell, ‘Melhoramento dos processos de produção de etanol de cana de açúcar. P,D&I’, 2019.

 https://doi.org/10.52202/069564-0153

[24] M. C. Palacios-Bereche, R. Palacios-Bereche, and S. A. Nebra, 'Comparison through exergy assessment of two alternatives for the energy use of vinasse : Concentration with incineration vs . Biodigestion', in *Proceedings of ECOS 2018 - The 31st International Conference on Efficiency, Cost, Optimisation, Simulation and Environmental Impact of Energy Systems*, 2018, pp. 1–14.

[25] M. C. Palacios-Bereche, A. C. Medina-jimenez, R. Palacios-Bereche, and S. A. Nebra, 'Comparison between two alternatives for the energy use of vinasse: Concentration-Incineration vs Biodigestion', in *Proceedings of the 17th Brazilian Congress of Thermal Sciences and Engineering*, 2018, pp. 1–13.

[26] J. Szargut, D. R. Morris, and F. R. Steward, *Exergy Analysis of Thermal, Chemical, and Metallurgical Processes*. New York, USA: Hemisphere Publishing Corporation, 1988.

[27] A. V. Ensinas and S. A. Nebra, 'Exergy Analysis as a Tool for Sugar and Ethanol Process Improvement', in *Handbook of Exergy, Hydrogen Energy and Hydropower Research*, G. Pélissier and A. Calvet, Eds. Nova Science Publishers, 2009, pp. 125–160.

[28] M. Modesto, S. A. Nebra, and R. J. Zemp, 'A Proposal to Calculate the Exergy of Non Ideal Mixtures Ethanol-Water Using Properties of Excess', in *14th European Biomass Conference*, 2005, no. October, pp. 1924–1927, doi: 88-89407-07-7.

[29] M. A. Lozano and A. Valero, 'Theory of the Exergetic Cost', *Energy*, vol. 18, no. 9, pp. 939–960, 1993.

[30] D. Ryan, A. Gadd, J. Kavanagh, and G. W. Barton, 'Integrated biorefinery wastewater design', *Chem. Eng. Res. Des.*, vol. 87, no. 9, pp. 1261–1268, 2009, doi: 10.1016/j.cherd.2009.04.016.