# Reduction of process steam demand and water-usage through heat integration in sugar and ethanol production from sugarcane – Evaluation of different plant configurations

**Eduardo A. Pina[1], Reynaldo Palacios-Bereche[1], Mauro F. Chavez-Rodriguez[2], Adriano V. Ensinas[1,3], Marcelo Modesto[1], Silvia A. Nebra[1,4]**

[1] Centre of Engineering, Modelling and Social Sciences (CECS/UFABC), Federal University of ABC, Av. dos Estados, 5001. CEP 09210-580, Santo André - SP - Brazil
reynaldo.palacios@ufabc.edu.br, adriano.ensinas@ufabc.edu.br, marcelo.modesto@ufabc.edu.br.

[2]Energy Planning Program, Universidade Federal do Rio de Janeiro (PPE/UFRJ), Rio de Janeiro, Brazil.
mfchavezr@gmail.com

[3] École Polytechnique Fédérale de Lausanne- STI-IGM-IPESE, Station 9, 1015-Lausanne, Switzerland

[4] Interdisciplinary Centre of Energy Planning (NIPE/UNICAMP), University of Campinas, Rua Cora Coralina, 330, CEP 13083-896, Campinas, SP, Brazil
silvia.nebra@pq.cnpq.br

**Abstract**

The sugarcane industry represents one of the most important economic activities in Brazil producing sugar and ethanol for the internal and external markets. There are also plants dedicated only to ethanol production. The aim of this study is to accomplish a joint assessment to evaluate the reduction of process steam demand and water usage obtained through heat integration and an exergy analysis to quantify the reduction in irreversibility generation owing to heat integration procedure. Two configurations of plant were analysed Case I - all sugarcane juice is destined to produce ethanol without sugar production and Case II - distribution of 50 %/50 % of total recoverable sugars in sugar and ethanol production. Simulations in ASPEN PLUS® software were performed in order to evaluate the mass and energy balances and heat integration using the Pinch Method was applied in order to minimize the utilities consumption. The results showed that heat integration promoted a reduction in steam consumption of 35% approximately, while the reduction in water consumption (water collecting requirement) was 24 and 13% in comparison to the conventional cases without heat integration.

**Keywords:** Ethanol, Sugar, Sugarcane, Heat Integration

**List of abbreviations**

BIGCC Biomass Integrated Gasification Combined Cycle

CCs Composite Curves

CHP Combined Heat and Power

EPE Empresa de Pesquisas Energéticas

GCC Grand Composite Curve

GHG Greenhouse Gases

H Enthalpy

LHV Low heating value

MEE Multiple Effect Evaporator

SMA Secretaria do Meio Ambiente

T* Shifted temperature

TRS Total recoverable sugars

## 1. Introduction

Over the recent years as energy security and environmental concerns have risen up various political agendas, there has been a substantial interest in biofuels and their potential contribution to energy security, mitigation of GHGs in the transport sector and also in delivering rural economic development benefits. Many countries around the world have developed or are developing biofuel mandates that require specific and rising contributions within the transport sector in the following years.

World fuel ethanol production in 2012 was estimated at about 107 billion L [1], from which approximately 49 % corresponded to the United States of America, the main world producer since 2006. For more than three decades (from mid-1970s to 2006) Brazil was the world's largest producer and consumer of ethanol. In 2012, the country figured in the third position, with a share of about 20 % (21.11 billion litres of ethanol). According to EPE [2], there has been an increase of 6.3 % in the national sugar production and an increase of 2.4 % in the national ethanol production from 2011 to 2012.

Most of the sugarcane plants in Brazil have been projected to produce both sugar and ethanol, prioritizing one over the other according to market prices. The decision of how to distribute and prioritize ethanol and sugar productions from sugarcane will definitely affect the process water and steam demands, which could have impacts on its sustainability, for example on their water consumption or GHG emissions balances.

Sugarcane plants projects are forced to improve water management, reducing water losses, closing circuits, and take advantage of water content in the own sugarcane (average of 700 litres of water in a tonne). Nowadays, in Sao Paulo State in Brazil, sugarcane-ethanol sector represents around 7% of superficial water withdrawals in the State, according to [3] it is estimated that currently the sector have an average water withdrawal of 1m$^3$/t of sugarcane which have been reduced drastically when compared to 5.6 m$^3$/t of sugarcane in the 1990s. Legislations, approved (Resolution SMA-88, 19/12/2008) establish regional division in the State, and approve new enterprises with a top of 1m$^3$/t of sugarcane in adequate regions, and only 0.7 m$^3$/ t of sugarcane in adequate regions with environmental restrictions. Another by-product of Brazilian sugarcane plants is electricity generated by their cogeneration systems. Plants with generating capacities exceeding 28 kWh/t of processed sugarcane are usually able to offer electricity surplus for sale to the public electricity grid. Several works have demonstrated the importance of reducing the energy consumption, namely steam, in the ethanol production process [4]. Such reduction will allow more surplus bagasse to be used either in the cogeneration system for electricity production, or in the second-generation ethanol production.

Heat integration and Exergy Analysis can be a powerful tool to achieve energy consumption optimization. According to Gundersen [5], process integration methods can be featured by the use of three main tools: heuristics, about design and economy; the use of optimization techniques and thermodynamics.

Heuristics techniques use different configuration scenarios and handle qualitative knowledge. For instance Moncada *et al*. [6] assess different conversion pathways in a sugar cane plant as function of feedstock distribution and technologies for sugar, ethanol, electricity and by-products production. On the other hand, Ensinas *et al*. [7] analysed steam demand reductions on two different configuration sugar cane plants and alternatives for the cogeneration systems, aiming at the surplus electricity generation increase. For water consumption reduction, Chavez-Rodriguez *et al*.[8] developed an heuristic method for a sugar cane plant, in which higher quality demand is supplied by available higher quality streams, complemented as necessary by the water from the treatment plant. This method showed to be suitable for handling the available information regarding the feed stream requirements for each process.

Optimization techniques can be divided into deterministic and non-deterministic methods [5]. Process integration techniques and multi-objective optimization have started to be applied recently in the last decade for biofuel production [9]. Ensinas *et al*. [10] performed a thermoeconomic optimization of the evaporation system and heaters network design in a sugarcane mil. Morandin *et al*. [11] applied optimization techniques to assess potential ways for energy integration improvement in a first generation sugar-cane plant, first focusing on the process only and then including a CHP system fuelled with the main process by-product. Furthermore, Ensinas *et al*. [12] applied a multi-objective optimization technique using evolutionary algorithms, in order to provide a set of solutions for a sugarcane ethanol distillery with 1st and 2nd generation processes in the same site using sugars and bagasse as feedstock respectively. Bechara *et al*. [13] applied optimization techniques to a stand-alone bagasse to ethanol plant, with the objective of minimizing the process's utility consumption for a fixed ethanol production rate.

Ahmetović *et al*. [14] performed an optimization of energy consumption in a corn-based ethanol plant and assessed its impact in water consumption, furthermore they used nonconvex nonlinear programming to minimize the total cost of water networks (which includes water reuse, water regeneration, recycling, local recycling around process) consisting of the cost of freshwater, the investment cost of treatment units, and the operating cost for the treatment units. Martín *et al*., [15], using similar methodology from [14] addressed water consumption optimization of second generation bioethanol production plants from lignocellulosic switch grass.

Finally, techniques such as Pinch Point [16] and Exergy Analysis focus on thermodynamics aspects of the process. Exergy studies on sugar cane plants started first than Pinch Analysis. Ensinas *et al*. [17]´s exergetic analysis shows that the highest contribution for the total irreversibility generation in a conventional sugarcane plant in Brazil were made by co-generation, juice extraction and fermentation systems. Modesto *et al*., [18] through an exergetic cost approach in a distillery of sugarcane showed the reduction of thermal energy consumption achieved by the insertion of diffusers as juice extraction technology. The combined production of sugar, ethanol and electricity for different configurations of the cogeneration plant has been analysed by Pellegrini *et al*. [19] and Pellegrini and de Oliveira Junior [20] using exergy-based costs. The lowest exergy-cost is achieved by pressurized biomass integrated gasification combined cycles

(BIGCC) compared with atmospheric BIGCC, super critical steam cycles, and traditional mills. Sosa-Arnao and Nebra, [21] focused exergetic analysis on bagasse boilers in order to identify improvement opportunities. Palacios-Bereche *et al*. [22] conducted an assessment of the exergy and exergetic cost associated with the ethanol production process from sugarcane biomass, including the route of bagasse enzymatic hydrolysis.

One of the first Pinch Point studies for the sugarcane industry in academic literature was made by Dias *et al*. [23] for an autonomous distillery, furthermore in Dias *et al*. [4] a similar analysis was made including different cogeneration configurations. On the other hand, Morandin *et al*. [11]´s Pinch analysis was applied for a joint production of sugar and ethanol. Palacios-Bereche *et al*. [24] extended the Pinch Analysis for ethanol production by enzymatic hydrolysis.

For a sugarcane distillery, Palacios-Bereche *et al*. [25] applied heat integration using Pinch Point Analysis for plant with a diffuser juice extraction system, furthermore in Palacios-Bereche *et al*. [26] this analysis was made considering mechanical vapour recompression integrated to the juice evaporation system. Pina *et al*. [27] also accomplished Pinch Analysis to an autonomous distillery and a sugar and ethanol plant evaluating the thermal demands and surplus electricity in each case while Martinez-Hernandez et al. [28] applied the Pinch Analysis, including Mass Pinch, to the ethanol production process from wheat. Finally, Albarelli *et al*. [29] performed a Pinch Point Analysis for a sugarcane plant integrated with a second generation process that used bagasse as feedstock; water demand reductions by heat integration were also quantified in [29].

The aim of this work is to accomplish a joint assessment to evaluate the reduction of process steam demand and water usage obtained through heat integration and an exergy analysis to quantify the reduction in irreversibility generation owing to heat integration procedure. Although there are several studies in literature about these analyses, there is not a joint assessment taking into account heat integration and exergy analysis applied to the cases studied in this work. For instance [29] accomplished a heat integration evaluation but they do not make an exergy analysis, on the other hand, [17] accomplished an exergetic analysis and heat integration through heuristic rules but they do not studied the reduction of water consumption owing to heat integration. Moreover, most of the studies do not mention details regarding the integration of evaporation system and their vapour bleedings. Two configurations of plant were analysed: Case I - all sugarcane juice is dedicated to produce ethanol without sugar production and Case II - equal distribution of total recoverable sugars (TRS) in sugar and ethanol production. These cases were adopted because they are representative of the Brazilian sugarcane sector. The autonomous distilleries were common at Program for ethanol times (Proalcool Program) which promoted the production of ethanol fuel. Regarding the combined production of sugar and ethanol (Case II), although there are changes in TRS distribution, the case 50% to sugar production/50% to ethanol production represents an average of the sector according to [31] Simulations in ASPEN PLUS® [30] software were performed in order to evaluate the mass and energy balances; heat integration using the Pinch Method was applied in order to minimize utilities consumption. Challenges were found for sugarcane plant simulation due to some sugarcane components which are not present in the simulator's database, for instance the fibre components: cellulose, hemicellulose and lignin.

## 2. Process description – Studied cases

### 2.1 Case I - Ethanol production process without sugar production

Figure 1 shows a simplified block diagram of the ethanol production process. The main parameters considered for the simulation correspond to a Brazilian standard size plant that according to [31] has mill capacity, 2,000,000 t cane/year; crushing rate, 500 t cane/hour; season operations hours, 4,000 hours/year.

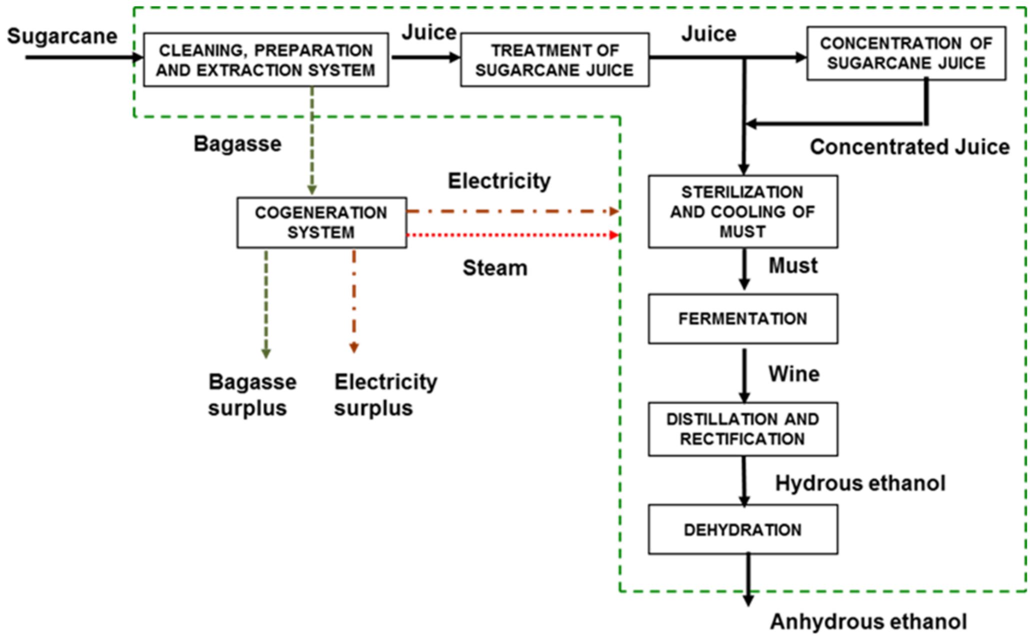



Figure 1: Simplified block flow of the ethanol production process from sugarcane.

For the detailed description of the conventional ethanol production process for the autonomous distillery the reader is referred to a previous study of the same authors [32].

Table 1: Equipment specifications for each operation process for Case I [22]

| Parameter | Value |
|---|---|
| ***Sugarcane cleaning, preparation and juice extraction*** | |
| Efficiency of soil removal in cleaning operation, % | 70 |
| Efficiency of sugar extraction in extraction system, % | 96.2 |
| Imbibition water, kg/t cane | 300 |
| Moisture content in bagasse, % | 50 |
| Mineral content in raw juice, % | 8.4 |
| ***Juice treatment*** | |
| Heating temperature of juice treatment, °C | 105 |
| Sucrose content in filter cake, % | 2 |
| Moisture content in filter cake, % | 70 |
| CaO consumption, kg/t cane | 0.5 |
| ***Juice Concentration*** | |
| Brix content in final must, % | 19 |
| Pressure 1$^{st}$ effect – Evaporation system, bar | 1.69 |

| | |
|---|---|
| Pressure 2nd effect – Evaporation system, bar | 1.31 |
| Pressure 3rd effect – Evaporation system, bar | 0.93 |
| Pressure 4th effect – Evaporation system, bar | 0.54 |
| Pressure 5th effect – Evaporation system, bar | 0.16 |
| ***Fermentation*** | |
| Conversion yield from sugars to ethanol, % | 89 |
| Fermentation temperature, °C | 34 |
| Yeast concentration in fermentation reactor, v/v% | 25 |
| Sulphuric acid for yeast treatment, kg/$m^3$ of ethanol | 5 |
| ***Distillation and rectification*** | |
| Number of stages in stripping section (column A) | 18 |
| Number of stages in rectification section (column A1) | 8 |
| Number of stages in top concentrator (column D) | 6 |
| Number of stages in phlegm rectification column (column B-B1) | 45 |
| Ethanol content in vinasse and phlegmasse, % | 0.02 |
| ***Dehydration*** | |
| Pressure in extractive column, bar | 1.01 |
| Pressure in recovery column, bar | 0.20 |
| Ethanol content in anhydrous ethanol, wt % | 99.4 |

Figure 2 shows a detailed block diagram of the autonomous distillery with some key data and variables used in simulation.

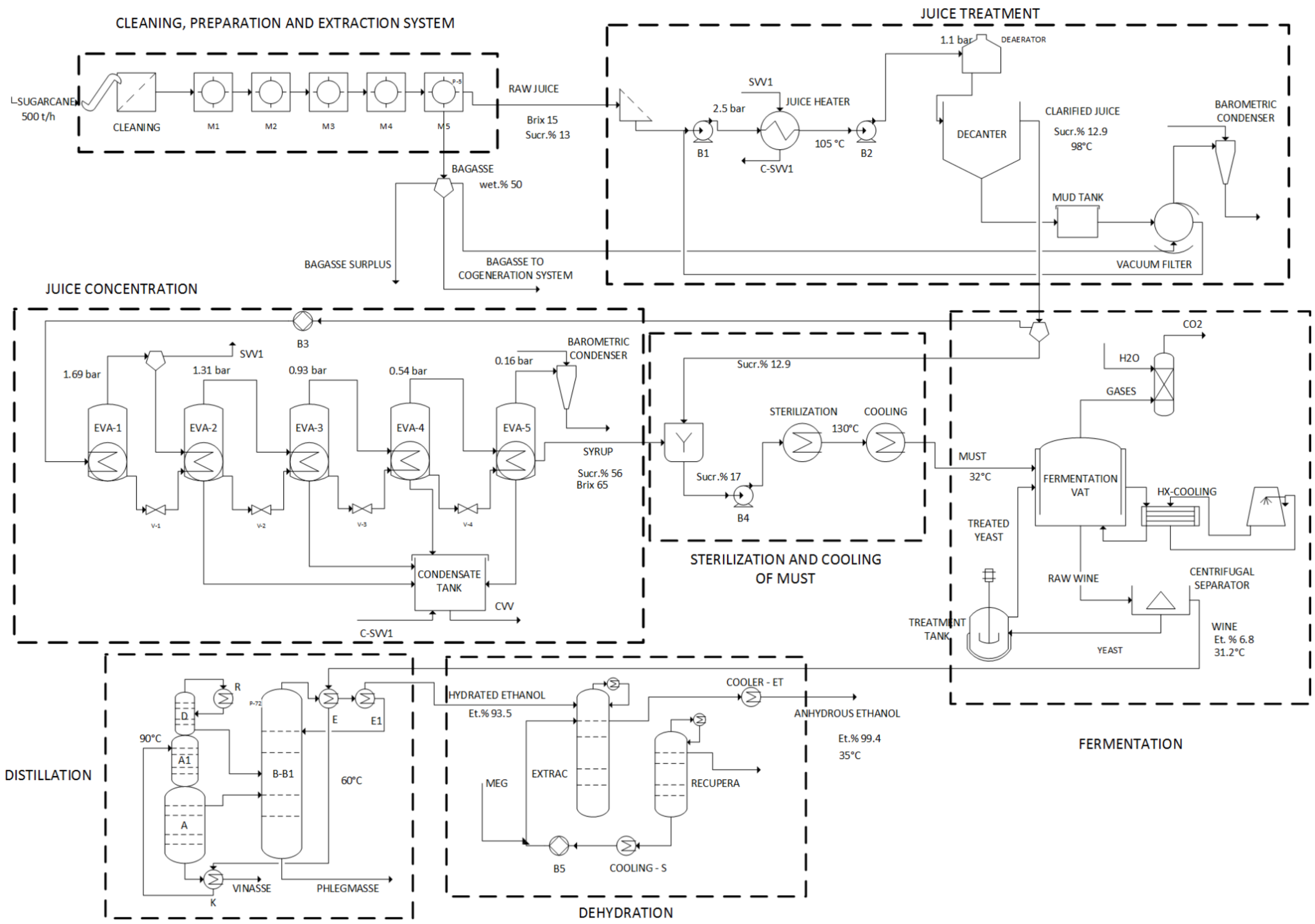



Figure 2: Detailed block diagram of the autonomous distillery

2.2 Case II - Ethanol and sugar production – Equal distribution TRS in sugar and ethanol production

Figure 3 shows the simplified block diagram for the plant in Case II. The cleaning, preparation and extraction system is the same that presented in the Case I.

Regarding the treatment of juice, in Case II the raw juice is separated in two parts. One part is treated for ethanol production, while the other is treated for sugar production. The difference is that the treatment for sugar production begins with the screening and the sulphitation process in order to remove some colour components of juice [33]. After that commonly there are the same treatments used for ethanol production: heating, liming, decantation, and mud filtration.

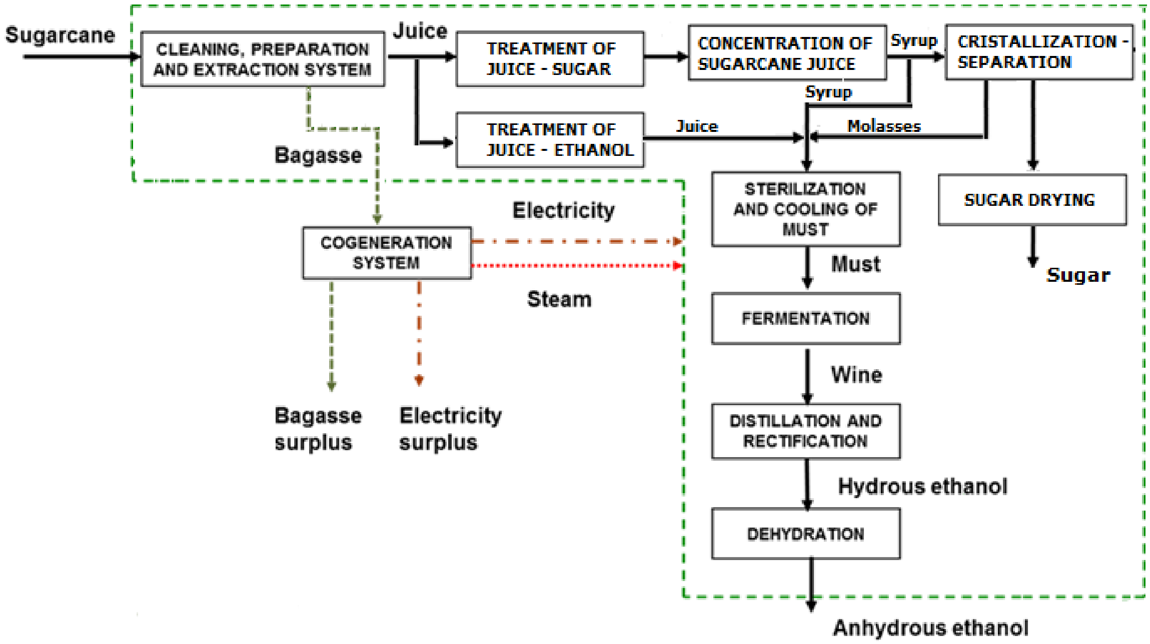



Figure 3: Scheme of the ethanol and sugar production process from sugarcane

The concentration of treated juice for sugar also takes place in a multiple-effect evaporation system of 5 effects until sucrose content of 55.4 % (syrup). Vapour bleedings with different pressures and temperatures resulting from the concentration process are used to cover heat demands in other parts of the plant. For this case, without consider the heat integration, vapour bleedings of first effect are used for heating in juice treatment and for heating the vacuum pans in crystallization step.

The syrup obtained in concentration step is sent to the crystallization process, which is accomplished in vacuum pans, in order to maintain low temperatures in massecuite [33], which has high content of soluble solids. In this way, problems of sucrose inversion can be avoided. Vapour bleeding from the first effect is used for heating vacuum pans. Then, sugar is separated from molasses through centrifugal separation.

Finally air at 100 ºC heated by turbines exhaust steam is used to reduce the sugar moisture content in the drying process.

For the ethanol production, the must for fermentation is prepared with juice, syrup and residual molasses. In Case II, the amounts of syrup and juice are determined in order to achieve a distribution of 50 %/50 % of TRS in sugar and ethanol production. Sugar concentration of must should not exceed 17 %.

The must sterilization and cooling as well as the fermentation, distillation and dehydration steps are the same that was assumed in Case I.

Table 2: Equipment specifications for each operation process for Case II [34]

| **Parameter** | **Value** |
|---|---|
| ***Crystallization process*** | |
| Operation pressure of vacuum pans, bar | 0.16 |
| Sugar A, kg/kg of sucrose in syrup | 0.78 |
| Brix of sugar A | 99.9 |
| Sucrose content in sugar A | 99.6 |
| Molasses produced, kg of molasses/kg of syrup | 0.286 |
| Brix of molasses | 74 |
| Purity f molasses | 70 |
| Sucrose recovered in molasses, % | 22 |
| Glucose recovered in molasses, % | 0.93 |
| Rate between vapour consumption in vacuum pans and vapour generated (kg | 1.32 |

| | |
|---|---|
| of heating vapour/kg of vapour generated) | |
| ***Drying of sugar*** | |
| Ambient air temperature, °C | 25 |
| Heated air, °C | 100 |
| Moisture content of sugar at the inlet of dryer, kg of water/kg wet sugar | 0.008 |
| Moisture content of sugar at the outlet of dryer, kg of water/kg wet sugar | 0.001 |

Figure 4 shows a detailed block diagram of the plant with combined production of sugar and ethanol. Some key data and variables used in simulation are presented in this diagram.

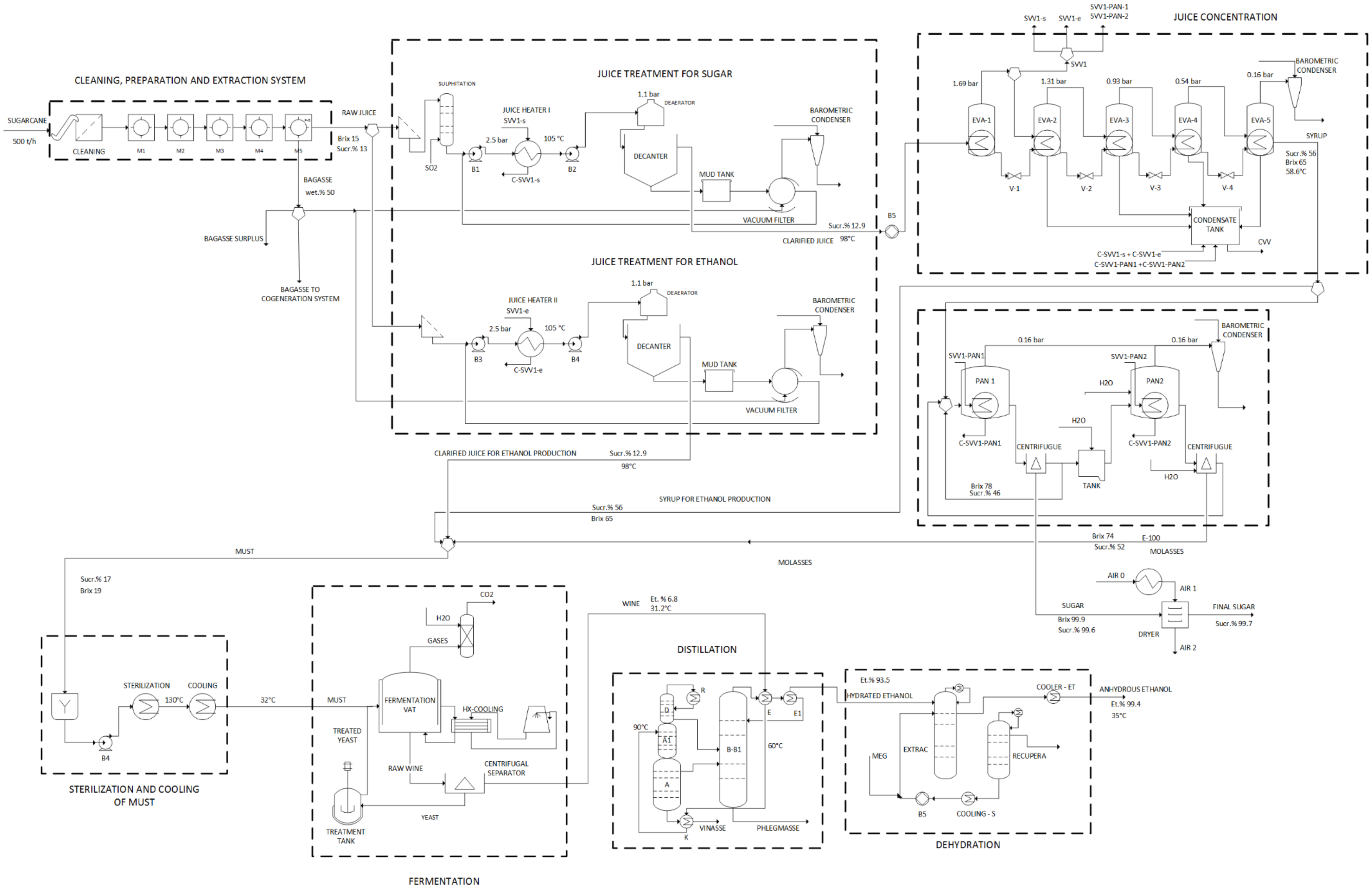



Figure 4: Detailed block diagram of the combined ethanol and sugar production

## 2.3 Cogeneration system

The cogeneration system in ethanol and sugar plants is commonly composed by a steam cycle using sugarcane bagasse as fuel in the boiler. Two cogeneration systems configurations were regarded in this study:

*Configuration I:* It is a steam cycle with back-pressure steam turbines. In this case, the production process determines the quantity of steam that can be produced by the boiler, once there is no condensation system. On the other hand there is a bagasse surplus.

*Configuration II:* This configuration is a steam cycle with extraction-condensing steam turbines. In this case, the condenser offers more operation options and higher flexibility, making it possible to operate all around the year [34].

Both configurations present a boiler with steam parameters of 530°C and 100 bar, and a juice extraction system with mills driven by electric engines. Steam turbines have an extraction at 6 bar for must sterilization and ethanol dehydration, and at 2.5 bar for the other heating requirements of the process such as the evaporation system, the reboilers of distillation columns (A and B-B1), and the air heater. The boiler and the cogeneration system were modelled according to previous studies [22]. Figure 5 shows the scheme of the cogeneration system for Configurations I and II.

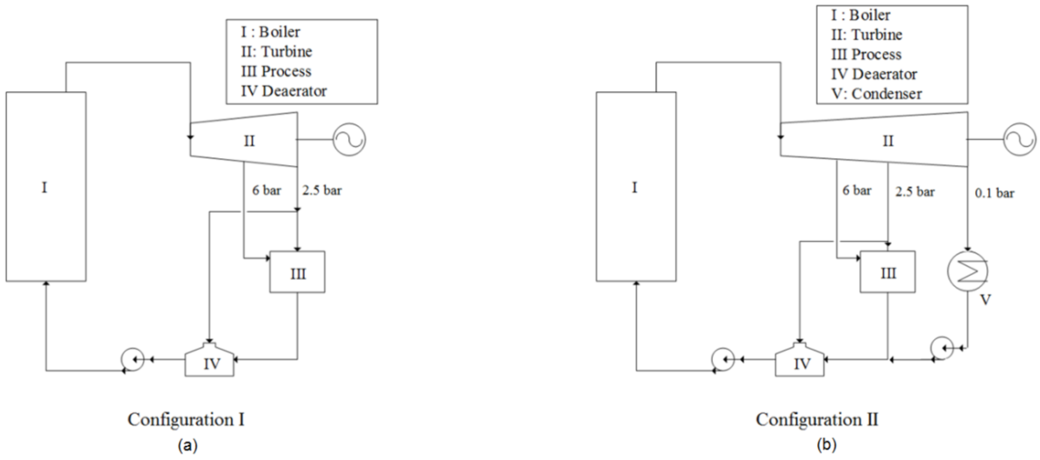



Figure 5: Scheme of cogeneration system: Configurations I and II

Table 3: Main specifications in cogeneration system [22]

| | |
|---|---|
| ***Cogeneration system*** | |
| Pressure of boiler live steam, bar | 100 |
| Temperature of boiler live steam, °C | 530 |
| Isentropic efficiency of electricity generation steam turbines, % | 80 |
| Alternator efficiency of turbine generator, % | 97.6 |
| Turbine mechanical efficiency, % | 98.2 |
| Pressure of condenser, bar | 0.1 |
| Pump isentropic efficiency, % | 70 |
| Boiler thermal efficiency, % (LHV base) | 86 |
| Mechanical power demand of cane preparation and extraction system, kWh/t of cane | 16 |
| Electric power demand of sugar and ethanol process, kWh/t of cane | 12 |

## 3 Methodology

### 3.1 Modelling and simulation in Aspen Plus software

Simulation of the process was carried out using Aspen Plus® software, according to the methodology used by Palacios-Bereche *et al*. [22]. The model selected for property calculations in the simulator depended on the operation type. In the cogeneration system, the Redlich-Kwong-Soave equation was adopted for properties calculation of combustion gases, it is necessary to model the bagasse boiler and according to [30] this state equation is appropriate for this type of calculations. On the other hand for water streams in steam cycle of cogeneration system the method Steam Tables was used.

For the sucrose-water solution (sugarcane juice), the UNIQUAC model was selected, with the binary parameters of Starzac and Malthouthi [35]. It was done because the default parameters of the simulator do not represent appropriately the behaviour of sucrose-water solution at equilibrium. Moreover it was necessary to create a subroutine in Fortran from empirical correlations [36] and link it to the simulator in order to calculate specific enthalpies for these solutions. It was performed because the sugarcane juice is a complex mixture of water, sucrose and impurities [33]. Finally, for ethanol mixtures in the distillation and dehydration steps, the UNIQUAC model was selected because according to the literature data [4] this model represents appropriately the behaviour of this mixture.

Regarding the components adopted in simulation, Table 3 shows the components adopted in this study. Some constituents of sugarcane are not found in the Aspen Plus ® database, thus they were created, and their properties inserted into the software, according to data from the literature [37].

Table 3: Components used in simulation

| Database components | |
|---|---|
| Silicon dioxide | Phosphoric acid |
| Water | Calcium hydroxide |
| Sucrose | Calcium phosphate |
| Glucose | Ammonia |
| Potassium oxide | Sulphuric acid |
| Aconitic acid | Glycerol |
| Potassium chloride | Acetic acid |
| Carbon dioxide | Succinic acid |
| Carbon monoxide | Isoamyl alcohol |
| Nitrogen | Ethanol |
| Oxygen | Sulphur dioxide |
| Hydrogen | Sulphurous acid |
| Nitrogen oxide | |
| **Created components** | |
| Cellulose | Lignin |
| Hemicellulose | Yeast |

To begin the modelling it was necessary to define the composition of sugarcane that arrives at the factory. Table 4 shows the sugarcane composition adopted in this study, which is according to [22]. Fibers were assumed as a mixture of solid components cellulose, hemicellulose, lignin. Reducing sugars were assumed as Glucose. Minerals were assumed as $K_2O$ and KCl and other non-saccharides as organic acids (aconitic and succinic acid). Soil was assumed as $SiO_2$.

Table 4: Sugarcane composition specified in simulation [22]

| Component | % Mass |
|---|---|
| Sucrose | 13.85 |
| Fibres | 13.15 |
| Reducing sugars | 0.59 |
| Minerals | 0.20 |
| Other non-saccharides | 1.79 |
| Water | 69.35 |
| Soil | 1.07 |

From these data and the specifications of tables 2 and 3, the energy and mass balances were accomplished using the Aspen Plus software [30] as a tool. Each component of the production process was modelled using the unit operations available in the software [22].

## 3.2 Pinch Analysis

Pinch Analysis was proposed by Linnhoff *et al*. [38] is a way to systematically identify heat recovery possibilities within a process setting targets for maximum achievable heat recovery at a certain minimum temperature difference. It has the purpose of reducing the use of external utilities to its minimum by combining the process hot and cold streams.

Its graphic tools, the Hot and Cold Composite Curves (CCs) and the Grand Composite Curve (GCC), simplify the identification of opportunities of Heat Integration [39] and are very useful for deeper understanding of the problem.

However, according to Higa et al. [40], the addition of a multiple effect evaporator (MEE) system presents a conceptual problem for the construction of both CCs and GCC, because the minimum target utility is greatly affected by certain arrangement. To solve such issue Urbaniec et al. [41] decomposed the thermal system into two sub-systems: the MEE and the remaining of the process.

Thus, the targets of minimum energy requirements were established according to the following procedure:

Step 1: Heat integration of available process streams excluding evaporation system and construction of the initial GCC. The process streams adopted for this step are presented in Table 5

Table 5: Hot and cold streams adopted for the process heat integration

| | Ti | Tf | ΔH (MW) | |
|---|---|---|---|---|
| | (ºC) | (ºC) | Case I | Case II |
| **Hot streams** | | | | |
| Sterilized juice | 130 | 32 | 41 | 17.1 |
| Wine from the vats | 32 | 28 | 12.2 | 6.2 |
| Phlegmasse | 103.9 | 35 | 3 | 1.4 |
| Vinasse | 109.3 | 35 | 37.2 | 16.1 |
| Anhydrous ethanol | 78.3 | 35 | 8.6 | 4.3 |
| Condensates of steam | 110 | 35 | 8.4 | 22.6 |
| Condensate column D | 84.9 | 35 | 19.5 | 9.9 |
| Condensate column B | 81.7 | 81.7 | 26.4 | 12.9 |
| Condenser extractive column | 78.3 | 78.3 | 7.4 | 3.7 |
| **Cold streams** | | | | |
| Imbibition water | 25 | 50 | 4.4 | 4.4 |
| Treatment juice | 34.2 | 105 | 44 | - |
| Treatment juice-etanol 1 | 42.1 | 105 | - | 10.2 |
| Treatment juice-sugar 1 | 35 | 70 | - | 14 |
| Treatment juice-sugar 2 | 73.3 | 105 | - | 15.6 |
| Juice pre-heating | 98.1 | 115 | 2.7 | 6.9 |
| Juice for sterilization | 95.5 | 130 | 14.6 | 5.7 |
| Final wine | 31.2 | 90 | 33.7 | 14.8 |
| Reboiler column A | 109.3 | 109.3 | 43.7 | 20.5 |
| Reboiler column B | 103.9 | 103.9 | 21.8 | 11.2 |
| Reboiler extractive column | 134.5 | 134.5 | 6.7 | 3.4 |
| Reboiler recuperative column | 149.6 | 149.6 | 2.5 | 1.3 |
| Sugar dryer | 25 | 100 | - | 0.32 |
| Syrup crystallization - pan1 | 66.2 | 82.2 | - | 26.7 |

| | | | | |
|---|---|---|---|---|
| Syrup crystallization - pan2 | 66.2 | 81.2 | - | 4.7 |

Step 2: In this step, the evaporation system is placed jointly with the initial GCC in a $T^*$- H diagram to identify possibilities of integration. The use of vapour bleedings from the evaporation system to cover heat demand of the process promotes further energy savings, thus in the case where there is not possible appropriate placement of evaporation system against GCC, the calculation of appropriate vapour bleedings in each effect of the evaporation system, according to the procedure proposed by [24], will be necessary. Figures 6a and 6b show the initial GCC against the evaporation system which is represented by horizontal bars (being each bar one effect). Figures 6c and 6d show the potential of vapour bleeding in each effect for Case I and II respectively. According to these figures above the Pinch Point, there is a potential to use bleedings from first effect in Case I and from first, second, third and fourth effect in Case II.

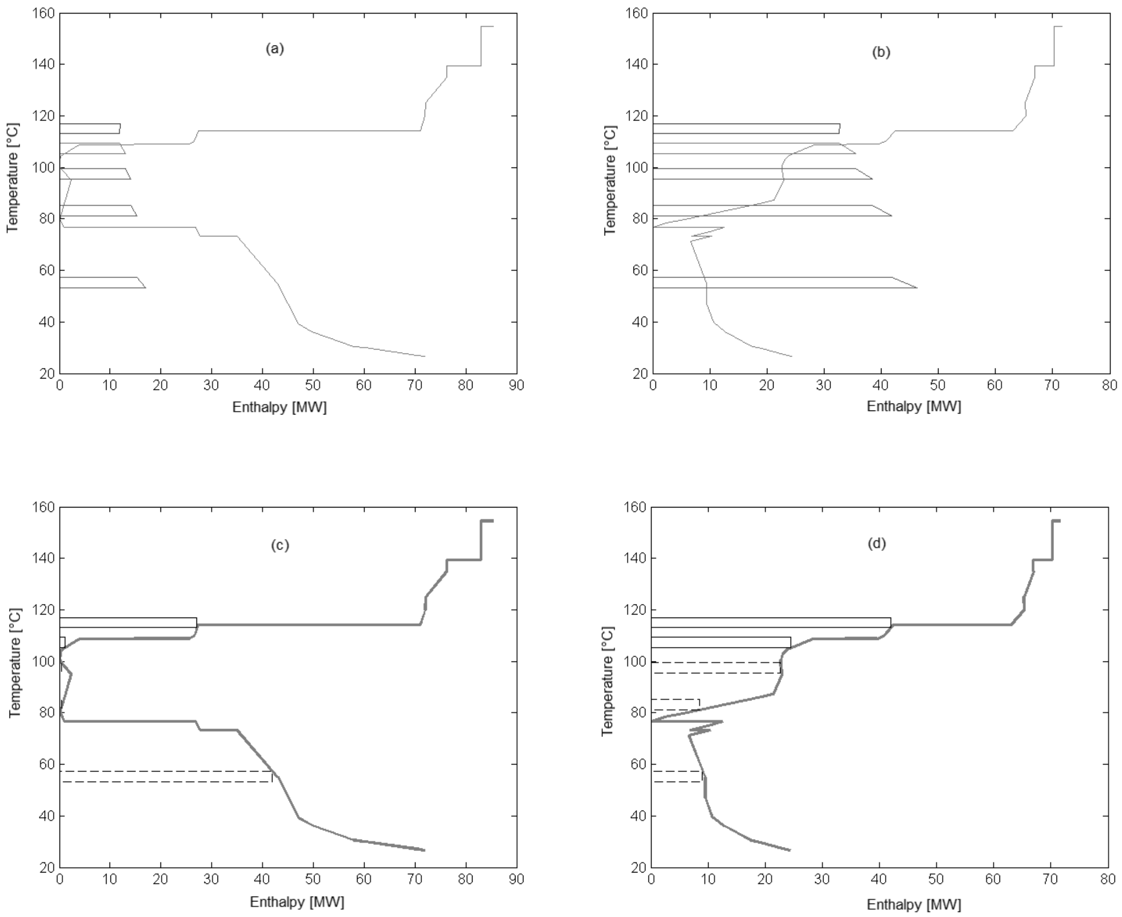



Figure 6: Initial GCC against Evaporation system for Case I (a) and II (b) – Vapour bleeding potential in each effect for Case I (c) and II (d)

It can be observed that for evaluated cases there was not possible to achieve an appropriate placement for an evaporator, then vapour bleedings were selected at first effect in Case I and at first and second effect in Case II according to figures 6c and 6d.

Step 3: After that, the evaporation system is simulated with the appropriate bleedings determined in Step 2. Finally, the evaporation system is integrated with the rest of the process, for that purpose the evaporation system streams are taking into account to construct the final GCC. Table 6 shows the evaporation system streams for Cases I and II.

Table 6: Evaporation system streams for heat integration including vapour bleedings

| Stream | Ti (°C) | Tf (°C) | ΔH (MW) | |
|---|---|---|---|---|
| | | | Case I | Case II |
| Juice 1st effect | 115 | 115 | 34,0 | 58,0 |
| Vapour 1st effect (VV1) | 115 | 115 | 34,1 | 57,9 |
| Juice 2nd effect | 107 | 107 | 7,0 | 38,7 |
| Vapour 2nd effect (VV2) | 107 | 107 | 7,8 | 41,2 |
| Juice 3rd effect | 98 | 98 | 7,8 | 41,2 |
| Vapour 3rd effect (VV3) | 98 | 98 | 8,5 | 43,8 |
| Juice 4th effect | 83 | 83 | 8,5 | 21,1 |
| Vapour 4th effect (VV4) | 83 | 83 | 9,4 | 23,4 |
| Juice 5th effect | 55 | 55 | 9,4 | 23,4 |
| Vapour 5th effect (VV5) | 55 | 55 | 10,8 | 26,8 |

Step 4: Update of the mass rates and temperatures of the evaporation system condensates. Return to Step 2 until convergence. Final GCCs are presented in Figure 7 at Results section. They were constructed from data presented in Table 5 and from heat flows of evaporation system of Table 6.

In this study, the minimum temperature difference ($\Delta T_{min}$) adopted was 10 ºC for the process streams and 4 ºC for the evaporation system streams.

In the present work, the construction of composite curves for Pinch Analysis was carried out through a plug-in implemented in C++ language. The plug-in is an auxiliary module to the main program of the "Virtual 1st Generation Sugarcane Plant", which is being developed using a Brazilian simulation platform called EMSO (Environment for Modelling, Simulation, and Optimization) and that will allow to compare and optimize different technological routes in the production of sugar, ethanol and bioelectricity.

### 3.3 Water use in sugar and ethanol production process

Water re-use has become a solution as a means of reducing the total amount of water intake. This, in turn, not only saves upstream treatment of raw water but also reduces wastewater treatment costs. Moreover heat integration promotes a reduction of cold utilities and consequently water use for cooling requirements. Thus, this part of the study estimates the potential reduction on water consumption owing to the heat integration for the two cases evaluated.

The water use in the industrial process was analysed considering all the process needs. To represent the water requirements, the first step was to register the water needs of a mill without any closed circuit according to Chavez-Rodriguez  et al. [42] and Mosqueira et al. [43]. The consumption rates reported were founded in the literature and also collected in real mills [3]. Table 7 shows the water needs in each simulated case.

Table 7: Water use in the mill (L/t of cane)

| Sub-System | Water Uses | Case I | Case II | Case $I_{TI}$ | Case $II_{TI}$ |
|---|---|---|---|---|---|
| Preparation and Extraction System | Imbibition | 300 | 300 | 300 | 300 |
| | Bearings Cooling | 50 | 50 | 50 | 50 |
| | Oil of Lubrication Cooling | 400 | 400 | 400 | 400 |
| Juice Treatment | Sulphitation cooling | - | 22 | - | 22 |
| | Preparing of milk lime | 8 | 23 | 8 | 23 |
| | Barometric Condensers of Filters | 214 | 214 | 214 | 214 |
| | Filter Cake Washing | 70 | 70 | 70 | 70 |
| | Polymer preparation for Settling | 15 | 15 | 15 | 15 |
| Juice Concentration | Barometric Condenser of Evaporation | 413 | 2,076 | 746 | 1,854 |
| Sugar production | Centrifugal washing | - | 17 | - | 17 |
| | Dilution of poor molasses | - | 2 | - | 2 |
| | Dilution of sugar | - | 9 | - | 9 |
| | Water added to pans | - | 3 | - | 3 |
| | Water for vacuum in the pans | - | 2,431 | - | 2,431 |
| | Crystallyzer cooling | - | 30 | - | 30 |
| Fermentation | Cooling of must for fermentation | 3,741 | 1,089 | 250 | 95 |
| | Cooling of fermentation vats | 2,000 | 1,747 | 2,000 | 1,747 |
| | Dilution of milk yeast | 141 | 122 | 141 | 122 |
| Distillation | Carbon Dioxide Scrubber for fermentation | 27 | 14 | 27 | 14 |
| | Condenser of Distillation Column | 1,679 | 853 | 913 | 853 |
| | Condenser of Rectification Column | 2274 | 1,111 | 0 | 758 |
| Dehydration | Condenser of Extraction Column | 637 | 319 | 637 | 319 |
| | Condenser of Recuperation Column | 106 | 87 | 106 | 87 |
| | Cooling of Solvent | 65 | 32 | 65 | 32 |
| | Cooling of Anhydrous Ethanol | 741 | 370 | 741 | 370 |
| Cogeneration System | Boiler Feed Water | 501 | 501 | 501 | 501 |
| | Cooling of Turbogenerators | 200 | 200 | 200 | 200 |
| Others | Washing Scrubber (boiler) | 1,002 | 1,002 | 1,002 | 1,002 |
| | General cleaning | 50 | 50 | 50 | 50 |
| | Drinkable uses | 30 | 30 | 30 | 30 |
| | | **14,664** | **13,188** | **8,466** | **11,619** |

It can be observed from Table 7 that refrigeration and condensing processes such as cooling of fermentation vats, barometric condenser of evaporation, condenser of distillation and vacuum in the pans are the major water users in the plant. Case I have the higher water needs; even though it does not have the same water needs as sugar production, like water for vacuum in pans, added for sugar, for dilution of molasses, etc.

this fact is explained by the big amounts of cooling needs for fermentation and distillation, supplied by cold water.

The second step was to identify and quantify water Sources to re-use such as condensates in sugar plant. Table 8 shows these "water sources". These currents might be needed to be treated, according their quality.

Table 8: Reuse potential water streams (L/t of cane)

| **Reuse water streams (L/t of cane)** | **Case I** | **Case II** |
|---|---|---|
| Condensate of filtration | 7 | 3 |
| Condensate of vapour - Evaporation system[1] | 143 | 527 |
| Condensate of 5th effect vapour in barometric condenser | 18 | 91 |
| Scrubber water blowdown | 50 | 35 |
| Cleaning water collected (50%) | 25 | 25 |
| Boiler blowdown | 20 | 35 |
| Water from dehydration process | 4 | 2 |
| Vinasse | 896 | 381 |
| Total | 1163 | 1099 |
| Total without vinasse | 267 | 718 |

[1]Condensate of the $1^{st}$, $2^{nd}$ $3^{rd}$ and $4^{th}$ effect.

Condensates of evaporation section could be re-used without treatment, for example in imbibition, as make-up water in cooling systems, etc. However, it can be observed that Vinasse is the greatest source of water to be re-used, but it needs treatments like evaporation, or reverse osmosis; due to its high load of suspended solids, Biochemical Oxygen Demand (BOD) and low pH. So, in this work, its re-use was not considered, as is usual nowadays.  The integrated cases presented values of reuse water similar to no integrated cases.

The third step is to simulate the closing of water circuits, which conducts to the effective collecting water needed to attend processes. Table 9 shows the losses in the closed circuits.

Table 9. Water Losses of Closed Circuits [33]

| Closed Circuits | Water Losses(%) |
|---|---|
| By Cooling Towers | 3% |
| Bearing Cooling | |
| Oil of Lubrification Cooling | |
| Sulfitation Cooling | |
| Cooling of juice for Fermentation | |
| Cooling of Fermentation Vats | |
| Cooling of Turbogenerators | |
| Cooling of Crystallizers | |
| Cooling of Solvent | |
| By Spray Ponds | 4% |
| Barometric Condenser of Evaporation | |
| Barometric Condensers of Filters | |
| Barometric Condensers in Pans | |
| Condenser of Distillation | |
| Condenser of Rectification | |
| Condenser of Extractive Column | |
| Condenser of Recuperation Column | |
| Treatment Washing Scrubbers Water | 5% |
| Recirculation Boiler Feed Water (blowdown) | 5% |

For the simulation, it was assumed that water return to spray ponds at 50ºC where it is cooled down to 30º and then used again. For cooling towers it was assumed water inlet at 30ºC and outlet at 25ºC.

The effective collecting of water occurs for the make-up of the closed circuits and also to attend demands of processes where it is added to the streams, as for example imbibition, yeast dilution, preparing of lime, etc. Table 10 shows the data of effective collected water needs.

Table 10. Effective water demand by process (L/t of cane)

| Sub-System | Effective water demanded by process | Case I | Case II | Case $I_{TI}$ | Case $II_{TI}$ |
|---|---|---|---|---|---|
| Preparation and Extraction System | Imbibition | 300 | 300 | 300 | 300 |
| | Make-up bearing cooling | 1.5 | 1.5 | 1.5 | 1.5 |
| | Make-up oil lubrification cooling | 12 | 12 | 12 | 12 |
| Juice Treatment | Make-up sulfitation cooling | - | 0.66 | - | 0.66 |
| | Lime preparation | 8 | 23 | 8 | 23 |
| | Make-up water for vacuum in the filter | 9 | 9 | 9 | 9 |
| | Filter cake washing | 70 | 70 | 70 | 70 |
| | Polymer preparation for Settling | 15 | 15 | 15 | 15 |
| Juice Concentration | Make-up of barometric condenser of evaporation | 17 | 83 | 30 | 74 |
| Sugar production | Centrifugue washing | - | 17 | - | 17 |
| | Dilution of poor molasses | - | 2 | - | 2 |
| | Dilution of sugar | - | 9 | - | 9 |
| | Water added to pans | - | 3 | - | 3 |
| | Make-up vacuum pan circuit | 0 | 97 | 0 | 97 |
| | Make-up crystallizer cooling | - | 1 | - | 1 |
| Fermentation | Make-up for ethanol juice cooling | 112 | 33 | 7 | 3 |
| | Make-up fermentation vat cooling | 60 | 52 | 60 | 52 |
| | Dilution milk of yeast | 141 | 122 | 141 | 122 |
| Distillation | Carbon Dioxide Scrubber for fermentation | 27 | 14 | 27 | 14 |
| | Make-up distillation condenser | 67 | 34 | 37 | 34 |
| | Make-up rectification condenser | 91 | 44 | 0 | 30 |
| Dehydration | Make-up extraction column condenser | 25 | 13 | 25 | 13 |
| | Make-up recuperation column condenser | 4 | 3 | 4 | 3 |
| | Make-up cooling of solvent | 3 | 1 | 3 | 1 |
| | Make-up cooling of anhydrous ethanol | 22 | 11 | 22 | 11 |
| Cogeneration System | Make-up boiler feed water | 25 | 25 | 25 | 25 |
| | Make-up turbogenerator cooling | 6 | 6 | 6 | 6 |
| Others | Make-up washing scrubber | 50 | 50 | 50 | 50 |
| | General cleaning | 50 | 50 | 50 | 50 |
| | Drinkable uses | 30 | 30 | 30 | 30 |
| | | **1,146** | **1,132** | **933** | **1,079** |

Conventionally, the water treatment system has to supply these quantities from the water collected in rivers, lakes, etc. As it is reported in Table 9, just closing circuits water consumption is reduced dramatically, reaching near 1 $m^3$/t of sugarcane, which is currently almost the average consumption in sugarcane plants [3].

If values of total effective collected water of Table 10 are subtracted from these of total water sources (Table 8), discounting vinasse, we obtain the net effective collecting as 0.878; 0.414; 0.665 and 0.361 $m^3$ of water/t of sugarcane for Case I, Case II, Case $I_{TI}$ and Case $II_{TI}$ respectively.

3.3 Exergy analysis

Exergy analysis was accomplished in order to evaluate the rate of irreversibility generation in each subsystem adopted. This assessment was done for integrated and no integrated cases to identify the potential of improvements resulting from heat integration.

Exergy of streams was calculated according to the procedure presented by [22]. Thus, the specific exergy can be calculated as the sum of physical and chemical exergy.

$$e = e^{PH} + e^{CH} \tag{1}$$

If the potential and kinetic components of exergy are neglected, the physical exergy can be calculated by the following expression:

$$e^{PH} = (h - h_0) - T_0(s - s_0) \tag{2}$$

The values of 25°C and 1 bar were taken as reference temperature and pressure. The Szargut *et al.* reference environment [49] is adopted for chemical exergy calculation. For solutions, chemical exergy is calculated by the following expression:

$$e^{CH} = \left(1/\overline{M}_{sol}\right)\left[\sum_{i=1}^{n} y_i.\tilde{\varepsilon}_i^0 + \overline{R}.T_0 \sum_{i=1}^{n} y_i.\ln a_i\right] \tag{3}$$

In Eq. 3, the first term represents the standard chemical exergy of the pure components ($\tilde{\varepsilon}_i^0$), and the second one, the exergy destruction from the dissolution process which is in function of the activity ($a_i$). The considerations and hypotheses for exergy calculation of solutions are the same as the presented in [22].

Finally, the rate of irreversibility generation can be calculated according to the following equation

$$I = \sum Ex_{in} - \sum Ex_{out,prod}$$

## 4 Results and discussion

Table 11 shows the main results of simulation of ethanol and sugar production from sugarcane.

Table 11: Products and steam consumption for the evaluated cases

| | **Case I** | **Case II** | **Case $I_{TI}$** | **Case $II_{TI}$** |
|---|---|---|---|---|
| Ethanol, (l/t of cane) | 80.4 | 40.1 | 80.4 | 40.1 |
| Sugar, (kg/t of cane) | 0 | 66.9 | 0 | 66.9 |
| Steam consumption, (kg/t of cane) | 467.7 | 465.4 | 308.1 | 294.6 |
| Effective water collecting requirement ($m_3$/t of cane) | 0.878 | 0.414 | 0.665 | 0.361 |

About the steam consumption the values for Case $I_{TI}$ and Case $II_{TI}$ were calculated from the targets of minimum energy requirements; it can be observed that heat integration promotes a significant reduction in steam consumption, which was 34% and 37% for Case $I_{TI}$ and Case $II_{TI}$ respectively in comparison to no integrated cases (Case I and Case II).

Regarding the effective water collecting requirement the heat integration promoted a further reduction of 24 and 13% in Case $I_{TI}$ and Case $II_{TI}$ respectively in comparison with the no integrated cases. It should be noted that values presented in Table 11 already takes into account the reuse and recycling of water presented in Section 3.3.

Tables 12 and 13 shows the results of simulation for Case I and II respectively.

### 4.1 Impacts in steam consumption, electricity surplus and bagasse surplus resulting from heat integration – Target analysis

Table 14 shows the steam consumption in each operation of the process for all cases. These values were obtained from targets of minimum energy requirements of Pinch Analysis. It can be observed that for both Cases I and II the major steam consumer is the evaporation system (35 and 69 % of the total respectively). In these cases the vapour bleedings are used for juice treatment (Case I and II) and for vapour pans (Case II). It can be noticed that there is no steam consumption for distillation column B-B1 in Case $I_{TI}$ and Case $II_{TI}$ owing to these heat requirements are covered by the process streams, which reduces significantly the total steam consumption. Case $II_{TI}$ presented the lowest total steam consumption, which indicates its high heat integration potential; it can be explained by its largest amount of vapour available for bleedings.

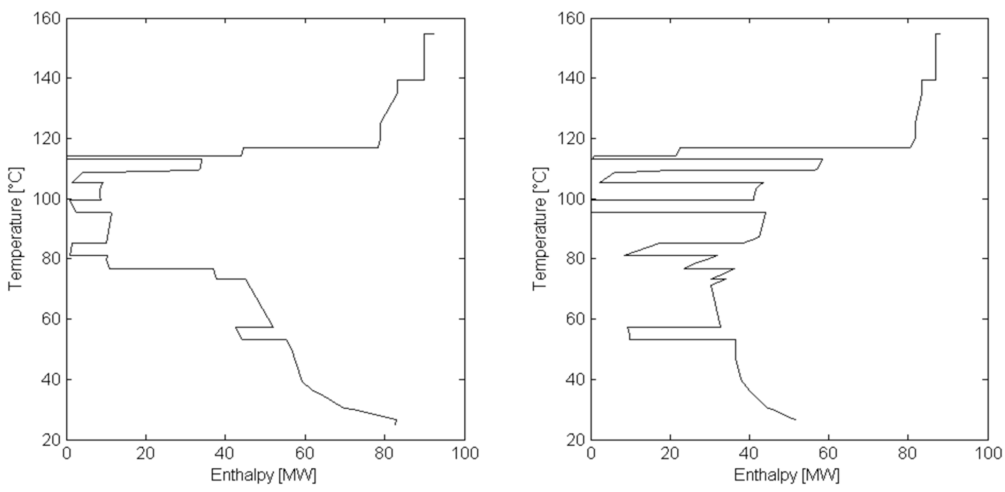
Figure 7 shows the final GCC for the Case $I_{TI}$ and Case $II_{TI}$ obtained through the heat integration procedure. Through the size of horizontal bars in GCC's it can be observed that heat exchanged in evaporator stages of Case $II_{TI}$ is higher than heat exchanged in Case $I_{TI}$. For this simulation the bleeding adopted in Case $I_{TI}$ was 44 t/h in first effect, while in Case $II_{TI}$ was 31 t/h in first effect and 36 t/h in third effect.

Table 14: Steam consumption (kg/t of cane)

| | | Case I | Case II | Case $I_{TI}$ | Case $II_{TI}$ |
|---|---|---|---|---|---|
| Steam 6 bar | Juice sterilization | 51.2 | 19.5 | 15.1 | 5.2 |
| | Dehydration: extractive column | 24.8 | 11.8 | 23.0 | 11.7 |
| | Dehydration: recovery column | 8.6 | 5.6 | 9.8 | 5.6 |
| Steam 2.5 bar | Pre-heating of juice | 0 | 0 | 3.6 | 22.8 |
| | Treatment juice- ethanol 1 | 0 | 0 | 0 | 1.9 |
| | Evaporation system | 164.2 | 322.3 | 112.3 | 191.4 |
| | Distillation column A | 147 | 67.7 | 144.3 | 54.8 |

| | | | | |
|---|---|---|---|---|
| Distillation column B-B1 | 71.9 | 37.2 | 0 | 0 |
| Drying sugar | 0 | 1.3 | 0 | 1.3 |
| TOTAL | 467.7 | 465.4 | 308.1 | 294.6 |

Case $I_{TI}$; Case $II_{TI}$: Cases thermally integrated




a b

Figure 7: Grand Composite Curves - GCC for the Case $I_{TI}$ (a) and Case $II_{TI}$ (b)

The changes in steam consumption of the plant result in variations on electricity and bagasse surplus depending on the type of cogeneration system adopted.

Figure 8 shows the bagasse and the electricity surplus for the evaluated cases with cogeneration system based on a steam cycle with backpressure steam turbines (Configuration I). The values presented in this figure were obtained from simulation of the cogeneration system presented in Figure 5a using data from Table 3. The amount of steam generated in the boiler is the necessary to match the needs of the process. It can be observed in Figure 8 that Configuration I promotes a larger amount of surplus bagasse when the steam consumption in the process is low, which happens in the integrated cases (Case $I_{TI}$ and Case $II_{TI}$). On the other hand the electricity surplus is lower for cases thermally integrated owing to the lower amount of steam that is passing through steam turbines.

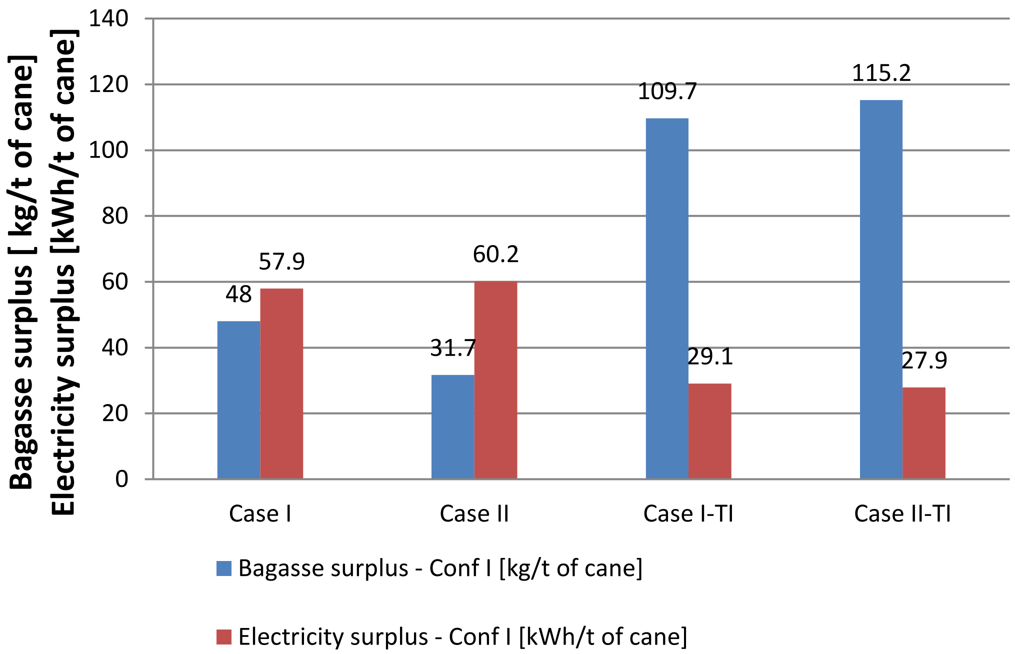



Figure 8: Bagasse and electricity surplus for the evaluated cases – Cogeneration system: Configuration I – Steam cycle with backpressure steam turbines

Figure 9 compares the electricity surplus for the evaluated cases and for the Configuration I and II of the cogeneration system. These values were obtained also from simulation of cogeneration systems presented in Figure 5.

In Configuration II all available bagasse is burnt in boiler, thus the steam generated is constant for all cases; there is not surplus bagasse for these cases. For the reason that the steam generated is higher than the steam for process, the excess goes through lower pressure stages of steam turbine producing more power.

From the results of Figure 9, it can be observed that cases with cogeneration system type configuration II presented similar electricity surplus. Only there is a slightly increase in electricity surplus resulting from the reduction in steam consumption promoted by heat integration. On the other hand, it can be observed that for integrated cases there is a significant difference in electricity surplus produced when Configuration I and II are compared.

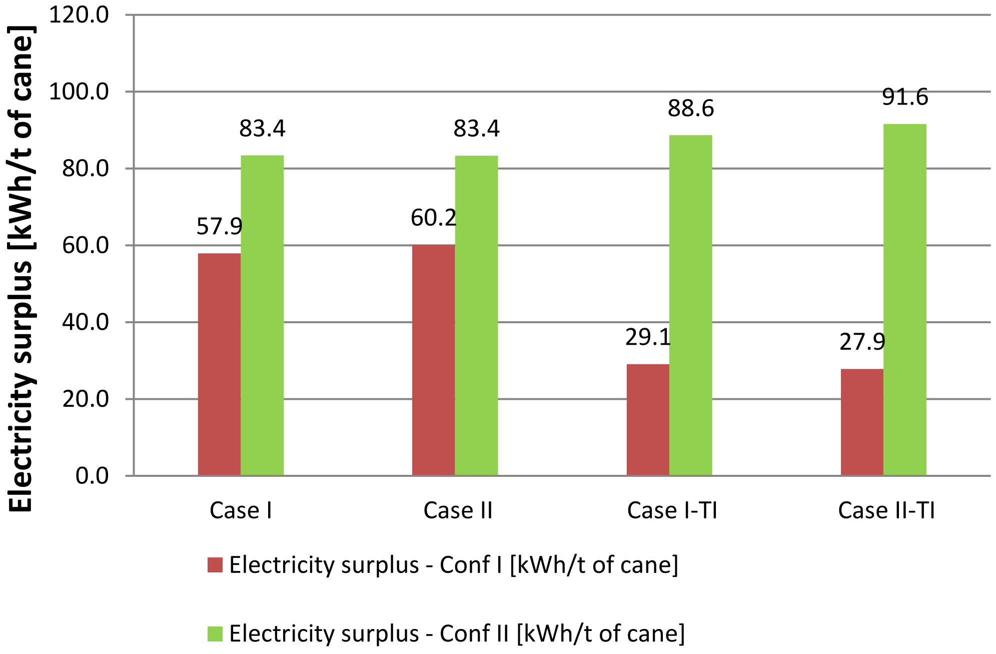



Figure 9: Electricity surplus for the evaluated cases

Production patterns in sugarcane plants prioritizing either ethanol or sugar production will depend on prices in the market. For instance, since 2013 with declining sugar prices, producers in Brazil have increased the share of TRS dedicated to ethanol production [44]. However it is not possible for an installed sugarcane plant that produces sugar and ethanol to change the production pattern from a Case II (50%/50% distribution of TRS) to a Case I (ethanol production only). Actually, on a campaign prioritizing ethanol, this mix can be changed at the edge to a 40%/60% pattern, 60% on ethanol and the rest on sugar due to capacity limits of the equipment.

Our results show that changes in the production patterns will not bring significant differences in steam consumption and electricity surplus. This allows flexibility to sugarcane plants which have electricity delivery commitments to the grid to secure the supply independently on their distribution of TRS among either sugar or ethanol.

Heat Integration allows increase in electricity surplus at least in 5.2 kWh/t sugarcane processed (Figure 9). Considering a sugar cane plant with a milling capacity of 12 000 t sugarcane/day (500 t/h) this electricity surplus means 2.6 MW in average of extra capacity sold to the grid. In the last years, low prices of ethanol and sugar have struggled the Brazilian sugar cane industry [45], however some plants have made profits selling electricity to the grid [46]. Nevertheless, heat integration (investment and installation of heat exchangers, pipelines, etc.) is likely to be implemented in greenfield sugarcane plants or in overhaul of the plant.

Actually electricity produced in sugar cane plants could be a key option to overcome current risk of energy rationing in Brazil [47] and to contribute to their climate change mitigation targets [48]. In that sense, not only financial incentives for investment in heat integration should be promoted but also to more efficient cogeneration plants in terms of electricity generation, such as Configuration II. As seen in Figure 9, for a plant which produces sugar and ethanol, a cogeneration system such as Configuration II produces 23.2 kWh/t of sugarcane more than Configuration I's. For a 12 000 t sugarcane/day-plant this means 11.6 MW in average of extra capacity without considering heat integration.

Heat Integration also contributes to the reduction of water consumption. For instance for an ethanol distillery (Case I), provided heat integration, consumptions in the make-up for cooling in fermentation and make-up for condenser in distillation are significantly reduced. Actually, if this distillery was located in an "adequate region" according to the Agro-environmental Zoning for sugar-ethanol sector [49], just with heat integration and closed water circuits it would be able to comply the limit of 1 $m^3$ of water consumption per ton of sugarcane processed of the legislation. In order to comply a limit of 0.7 $m^3$ of water consumption per ton of sugarcane processed, such as for "adequate regions with environmental restrictions", sugarcane plants would require in addition re-using internal water streams techniques [42].

Given these environmental and energy advantages of heat integration, further studies are suggested to assess cost and the economic feasibility of heat integration projects in sugarcane plants. Furthermore, if there is an economic potential for heat integration, financial mechanism and incentive for sugarcane plants´ owners are needed to be proposed in order to develop the market potential.

## 4.2 Exergy analysis

To accomplish the exergy analysis, it was necessary to calculate the exergy for each flow. Tables 12 and 13 show the flow information obtained from converged simulation for no integrated cases I and II respectively (Figures 2 and 3).

Table 12: Flow description for Case I - Cogeneration type Configuration I

| | Description | m (kg/s) | T (°C) | P (bar) | Brix | w (%) | ex (kJ/kg) |
|---|---|---|---|---|---|---|---|
| 1 | Sugarcane | 138.9 | 25 | 1 | 16 | - | 5762 |
| 2 | Bagasse produced in extraction system | 38.4 | 30 | 1 | 3 | - | 9979 |
| 3 | Bagasse for cogeneration | 29.8 | 30 | 1 | 3 | - | 9979 |
| 4 | Bagasse for filters | 0.7 | 30 | 1 | 3 | - | 9979 |
| 5 | Raw juice | 140.4 | 30 | 1 | 15 | - | 2697 |
| 6 | Treated juice | 141.5 | 98 | 1 | 15 | - | 2660 |
| 7 | Treated juice for concentration | 38.6 | 98 | 1.69 | 15 | - | 2660 |
| 8 | Treated juice for must preparation | 102.9 | 98 | 1.69 | 15 | - | 2660 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 9 | Syrup | 8.9 | 59 | 0.16 | 65 | - | 11424 |
| 10 | Must | 111.8 | 32 | 6 | 19 | - | 3370 |
| 11 | Wine | 145.2 | 31 | 1 | - | 6 | 2162 |
| 12 | Hydrated ethanol | 9.5 | 82 | 1.16 | - | 94 | 27635 |
| 13 | Second grade alcohol | 0.2 | 34 | 1.34 | - | 91 | 26916 |
| 14 | Vinasse | 124.4 | 77 | 1.46 | - | 0.02 | 386.2 |
| 15 | Phlegmasse | 10.8 | 108 | 1.34 | - | 0.03 | 113.9 |
| 16 | Anhydrous ethanol | 9.0 | 78 | 1 | - | 99 | 29435 |
| 17 | Imbibition water | 41.7 | 50 | 1 | - | - | 54 |
| 18 | Water for polymer dilution | 2.1 | 25 | 1 | - | - | 50 |
| 19 | Water for filter cake washing | 9.7 | 80 | 1.5 | - | - | 69 |
| 20 | Water for $Ca(OH)_2$ dilution | 1.1 | 25 | 1 | - | - | 50 |
| 21 | Water for fermentation gases washing | 3.8 | 25 | 1 | - | - | 50 |
| 22 | Water for yeast dilution | 19.9 | 29 | 1 | - | - | 50 |
| 23 | Boiler blowdown | 2.8 | 29 | 1 | | | 50 |
| 24 | Make-up water for boiler | 2.8 | 29 | 1 | | | 50 |
| 25 | Condensate of filter cake washing | 1 | 69 | 0.3 | - | - | 363 |
| 26 | Water shortfall in condensate tank | 27.4 | 25 | 1 | | | 50 |
| 27 | Make up water for general uses | 109.6 | | | | | 50 |
| 28 | Water recovery from dehydration | 0.5 | 60.8 | 0.2 | - | - | 306 |
| 29 | Vapour bleed VV1 for heating use | 19.9 | 116.1 | 1.69 | - | - | 616 |
| 30 | Steam for distillation column | 20.4 | 127 | 2.5 | - | - | 668 |
| 31 | Steam for rectification column | 10.0 | 127 | 2.5 | - | - | 668 |
| 32 | Steam for dehydration column (extractive) | 3.4 | 159 | 6 | - | - | 796 |
| 33 | Steam for dehydration column (recovery) | 1.2 | 159 | 6 | - | - | 796 |
| 34 | Steam for juice concentration | 22.8 | 127 | 2.5 | - | - | 668 |
| 35 | Steam for must sterilization | 7.1 | 159 | 6 | - | - | 796 |
| 36 | Vapour of 5th effect | 2.5 | 59 | 0.16 | - | - | 56 |
| 37 | Steam for process (2.5 bar) | 53.2 | 127 | 2.5 | - | - | 668 |
| 38 | Steam bleed for process (6 bar) | 11.8 | 159 | 6 | - | - | 796 |
| 39 | Condensate of vapour bleeds (VV1) | 19.9 | 115 | 1.69 | - | - | 98 |
| 40 | Condensate of exhaust steam - Distillation column | 20.4 | 127 | 2.5 | - | - | 111 |
| 41 | Condensate of exhaust steam - Rectification column | 10.0 | 127 | 2.5 | - | - | 111 |
| 42 | Condensate of steam bleed - Dehydration column | 3.4 | 159 | 6 | - | - | 149 |
| 43 | Condensate of steam bleed - Recovery column | 1.2 | 159 | 6 | - | - | 149 |
| 44 | Condensate of exhaust steam - Juice concentration | 22.8 | 127 | 2.5 | - | - | 111 |
| 45 | Condensate of steam bleed - Must sterilization | 7.1 | 159 | 6 | - | - | 149 |
| 47 | Vapour condensates CVV (total) | 27.1 | 83.2 | 0.5 | - | - | 71 |
| 48 | Condensate (6 bar) | 11.8 | 159 | 6 | - | - | 149 |
| 49 | Condensate (2.5 bar) | 53.2 | 127 | 2.5 | - | - | 111 |
| 50 | CaO | 0.07 | 25 | 1 | - | - | 1965 |
| 51 | Sulphuric acid | 0.06 | 29 | 1 | - | - | 1666 |
| 53 | Steam generated at boiler | 66.3 | 530 | 100 | - | - | 1509 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 54 | Water withdrawal | 159.2 | 25 | 1 | | | 50 |

Table 13: Flow description for Case II - Cogeneration type Configuration I

| | Description | m (kg/s) | T (°C) | P (bar) | Brix | w % | ex |
|---|---|---|---|---|---|---|---|
| 1 | Sugarcane | 138.9 | 25 | 1 | 16 | - | 5762 |
| 2 | Bagasse produced in extraction system | 38.4 | 30 | 1 | 3 | - | 9979 |
| 3 | Bagasse for cogeneration | 31.6 | 30 | 1 | 3 | - | 9979 |
| 4 | Bagasse for filters | 0.7 | 30 | 1 | 3 | - | 9979 |
| 5 | Raw juice | 140.4 | 30 | 1 | 15 | - | 2697 |
| 6 | Treated juice for concentration (sugar) | 109.7 | 98 | 1.69 | 15 | - | 2660 |
| 7 | Treated juice for must preparation (ethanol) | 36.6 | 98 | 1.69 | 15 | - | 2660 |
| 8 | Syrup | 23.9 | 59 | 0.16 | 65 | - | 11424 |
| 9 | Syrup for sugar | 21.2 | 59 | 0.16 | 65 | - | 11424 |
| 10 | Syrup for ethanol | 2.6 | 59 | 0.16 | 65 | - | 11424 |
| 11 | Molasses | 6.1 | 91 | 6 | 74 | - | 13012 |
| 12 | Sugar-A | 9.3 | 86 | 1 | 99.9 | - | 17537 |
| 13 | Air ambient | 4.4 | 25 | 1 | - | - | - |
| 14 | Sugar | 9.3 | 44 | 1 | | - | 17551 |
| 15 | Humid air | 4.5 | 44 | 1 | - | - | - |
| 16 | Must | 45.3 | 32 | 6 | 25 | - | 4419 |
| 17 | Wine | 60.8 | 31 | 1 | - | 7 | 2555 |
| 18 | Hydrated ethanol | 4.7 | 82 | 1.16 | - | 94 | 27635 |
| 19 | Second grade alcohol | 0.1 | 34 | 1.34 | - | 91 | 26916 |
| 20 | Vinasse | 52.9 | 77 | 1.46 | - | 0.004 | 550 |
| 21 | Phlegmasse | 5.0 | 108 | 1.34 | - | 0.04 | 98 |
| 22 | Anhydrous ethanol | 4.4 | 78 | 1 | - | 99 | 29435 |
| 23 | Imbibition water | 41.7 | 50 | 1 | - | - | 54 |
| 24 | Water for polymer dilution | 2.1 | 25 | 1 | - | - | 50 |
| 25 | Water for filter cake washing | 9.7 | 80 | 1.5 | - | - | 69 |
| 26 | Water for Ca(OH)2 dilution | 3.2 | 25 | 1 | - | - | 50 |
| 27 | Water for fermentation gases washing | 1.9 | 25 | 1 | - | - | 50 |
| 28 | Water for yeast dilution | 16.9 | 29 | 1 | - | - | 50 |
| 29 | Boiler blowdown | 4.9 | 29 | 1 | - | - | 50 |
| 30 | Make-up water for boiler | 4.9 | 29 | 1 | - | - | 50 |
| 31 | Condensate of filter cake washing | 1 | 69 | 0.3 | - | - | 363 |
| 32 | Water shortfall in condensate tank | -12.3 | 25 | 1 | - | - | 50 |
| 33 | Make up water for general uses | 151.9 | 25 | 1 | - | - | 50 |
| 34 | Water recovery from dehydration | 0.3 | 60.8 | 0.2 | - | - | 306 |
| 35 | Vapour bleed V1 for heating use | 32.2 | 116.1 | 1.69 | - | - | 616 |
| 36 | Steam for distillation column | 9.4 | 127 | 2.5 | - | - | 668 |
| 37 | Steam for rectification column | 5.2 | 127 | 2.5 | - | - | 668 |
| 38 | Steam for dehydration column (extractive) | 1.6 | 159 | 6 | - | - | 796 |
| 39 | Steam for dehydration column (recovery) | 0.8 | 159 | 6 | - | - | 796 |
| 40 | Steam for juice concentration | 44.8 | 127 | 2.5 | - | - | 668 |
| 41 | Steam for must sterilization | 2.7 | 159 | 6 | - | - | 796 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 42 | Steam for sugar dryer | 0.2 | 127 | 2.5 | - | - | 668 |
| 44 | Steam for process (2.5 bar) | 59.5 | 127 | 2.5 | - | - | 668 |
| 45 | Steam bleed for process (6 bar) | 5.1 | 159 | 6 | - | - | 796 |
| 46 | Condensate of vapour bleeds (VV1) | 32.2 | 115 | 1.69 | - | - | 98 |
| 47 | Condensate of exhaust steam - Distillation column | 9.4 | 127 | 2.5 | - | - | 111 |
| 48 | Condensate of exhaust steam - Rectification column | 5.2 | 127 | 2.5 | - | - | 111 |
| 49 | Condensate of steam bleed - Dehydration column | 1.6 | 159 | 6 | - | - | 149 |
| 50 | Condensate of steam bleed - Recovery column | 0.8 | 159 | 6 | - | - | 149 |
| 51 | Condensate of exhaust steam - Juice concentration | 44.8 | 127 | 2.5 | - | - | 111 |
| 52 | Condensate of steam bleed - Must sterilization | 2.7 | 159 | 6 | - | - | 149 |
| 53 | Condensate of exhaust steam - Sugar dryer | 0.2 | 127 | 2.5 | - | - | 111 |
| 55 | Vapour condensates CVV (total) | 73.2 | 108.3 | 0.5 | - | - | 92 |
| 56 | Condensate (6 bar) | 5.1 | 159 | 6 | - | - | 149 |
| 57 | Condensate (2.5 bar) | 59.5 | 127 | 2.5 | - | - | 111 |
| 58 | CaO | 0.13 | 25 | 1 | - | - | 1965 |
| 59 | Sulphuric acid | 0.001 | 29 | 1 | - | - | 1666 |
| 60 | Sulfur dioxide | 0.06 | 70 | 1 | - | - | 4892 |
| 61 | Steam generated at boiler | 66.7 | 530 | 100 | - | - | 1509 |
| 62 | Water withdrawal | 157.2 | 25 | 1 | - | - | 50 |
| 74 | Vapour bleed for juice treatment V1 | 18 | 116.1 | 1.69 | - | - | 616 |
| 75 | Condensate of vapour bleed for juice treatment V1 | 18 | 115 | 1.69 | - | - | 98 |
| 76 | Vapour bleed for vapour pan | 14.2 | 116.1 | 1.69 | - | - | 616 |
| 77 | Condensate of vapour bleed for vapour pan | 14.2 | 115 | 1.69 | - | - | 98 |
| 78 | Water for centrifugal washing | 2.4 | 25 | 1 | - | - | 50 |
| 79 | Water for dilution door molasses | 0.3 | 25 | 1 | - | - | 50 |
| 80 | Water for dilution of sugar | 1.3 | 25 | 1 | - | - | 50 |
| 81 | Water added to pans | 0.4 | 25 | 1 | - | - | 50 |

In order to evaluate the integrated cases $I_{TI}$ and $II_{TI}$, it was necessary to build a preliminary heat exchanger network. Figures 10 and 11 show the flow sheet of integrated cases.

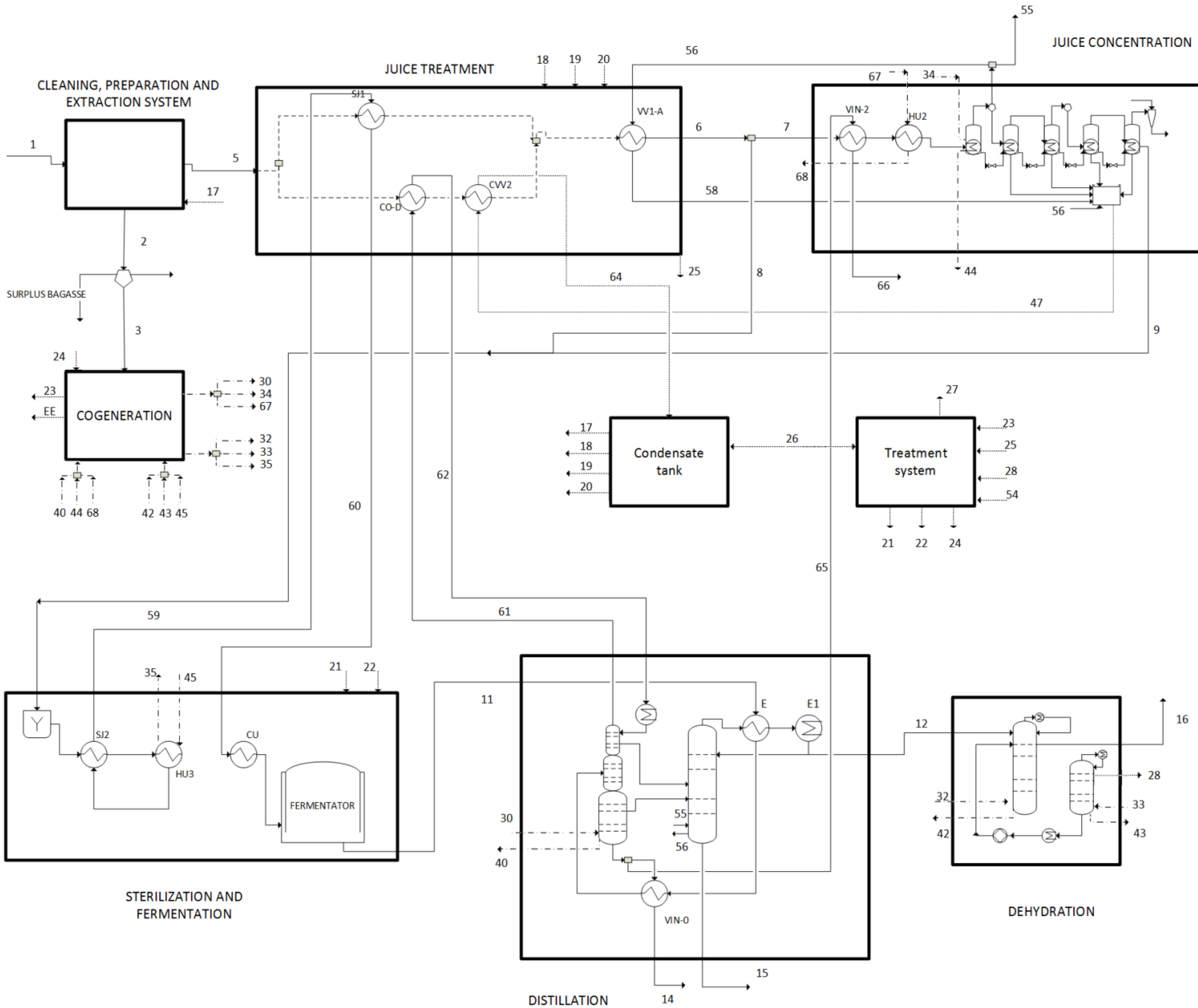



Figure 10. Flow sheet for Case $I_{TI}$

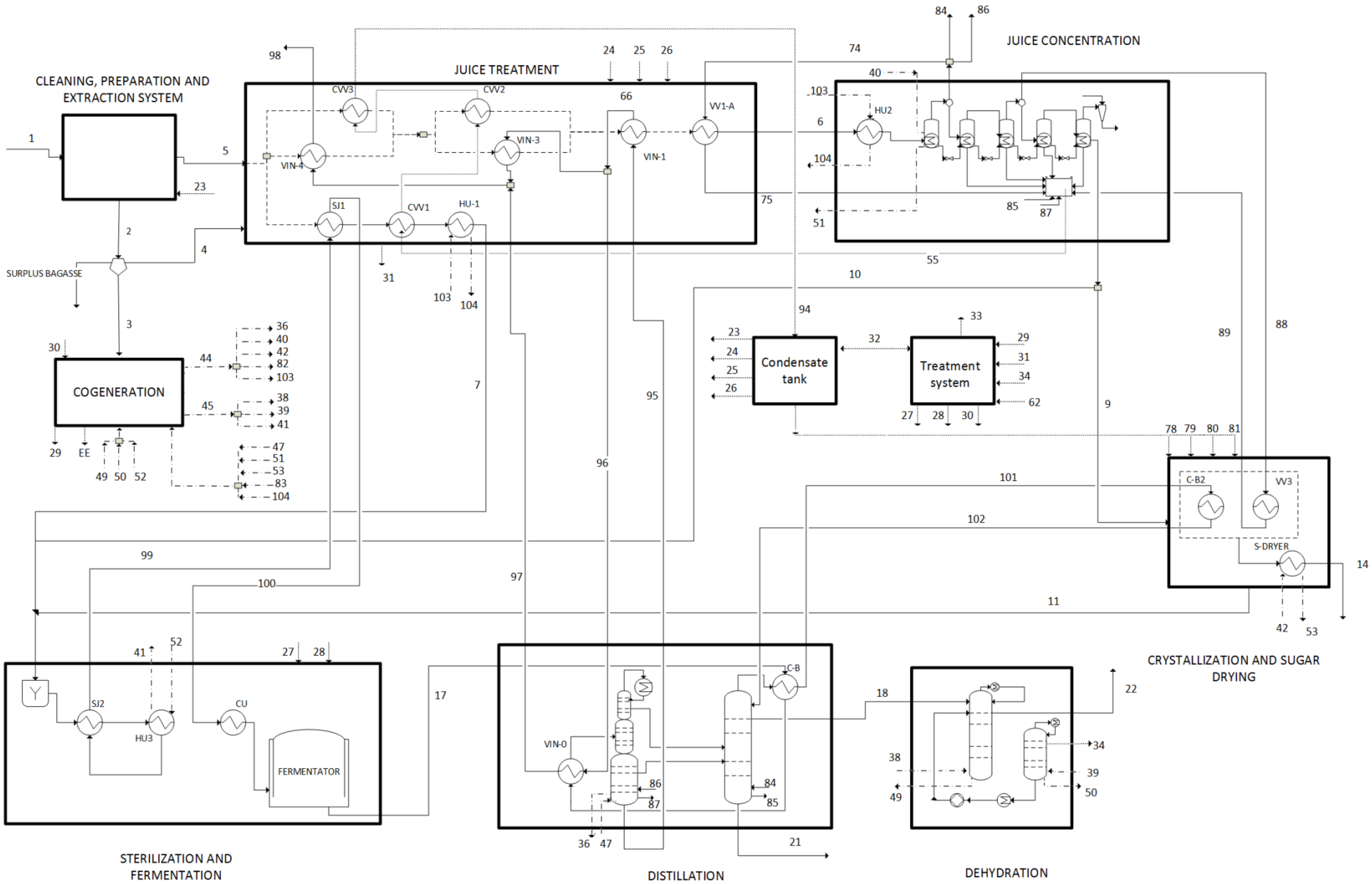



Figure 11. Flow sheet of Case $II_{T\ I}$

Tables 14 and 15 show the flow information for cases $I_{TI}$ and $II_{TI}$. Owing to the existence of several values, mainly process streams, that are the same as the respective values in no integrated cases (tables 12 and 13), tables 14 and 15 only present the values that changed owing to heat integration.

Table 14: Flow description for Case $I_{TI}$ – Cogeneration type Configuration I

| | Description | m (kg/s) | T (°C) | P (bar) | Brix | w % | ex |
|---|---|---|---|---|---|---|---|
| 3 | Bagasse for cogeneration | 20.8 | 30.1 | 1 | 3 | | 9979 |
| 14 | Vinasse-1 | 87.9 | 87 | 1.46 | - | 0.02 | 391.5 |
| 27 | Make up water for general uses | 80.0 | 25 | 1 | - | - | 50 |
| 29 | Vapour bleed VV1 total | 12.2 | 116 | 2 | - | - | 616 |
| 30 | Steam for distillation column | 20.0 | 127 | 3 | - | - | 668 |
| 32 | Steam for dehydration column (extractive) | 3.2 | 159 | 6 | - | - | 796 |
| 33 | Steam for dehydration column (recovery) | 1.4 | 159 | 6 | - | - | 796 |
| 34 | Steam for juice concentration | 15.6 | 127 | 3 | - | - | 668 |
| 35 | Steam for must sterilization | 2.1 | 159 | 6 | - | - | 796 |
| 37 | Steam for process (2.5 bar) | 36.1 | 127 | 3 | - | - | 668 |
| 38 | Steam bleed for process (6 bar) | 6.7 | 159 | 6 | - | - | 796 |
| 39 | Condensate of vapour bleeds (VV1) | 12.2 | 115 | 2 | - | - | 98 |
| 40 | Condensate of exhaust steam - Distillation column | 20.0 | 127 | 3 | - | - | 111 |
| 42 | Condensate of steam bleed - Dehydration column | 3.2 | 159 | 6 | - | - | 149 |
| 43 | Condensate of steam bleed - Recovery column | 1.4 | 159 | 6 | - | - | 149 |
| 44 | Condensate of exhaust steam - Juice concentration | 15.6 | 127 | 3 | - | - | 111 |
| 45 | Condensate of steam bleed - Must sterilization | 2.1 | 159 | 6 | - | - | 149 |
| 47 | Vapour condensates CVV (total) | 27.1 | 110 | 0.5 | - | - | 93 |
| 48 | Condensate (6 bar) | 6.7 | 159 | 6.0 | - | - | 149 |
| 49 | Condensate (2.5 bar) | 36.1 | 127 | 2.5 | - | - | 111 |
| 53 | Steam generated at boiler | 43.9 | 530 | 100 | - | - | 1509 |
| 54 | Water withdrawal | 129.6 | 25 | 1 | | | 50 |
| 55 | Vapour bleed VV1 to reboiler B-B1 | 9.8 | 116.1 | 1.69 | - | - | 616 |
| 56 | Vapour bleed VV1 to juice treatment | 2.4 | 116.1 | 1.69 | - | - | 616 |
| 57 | Condensate of VV1 from reboiler B-B1 | 9.8 | 115 | 2 | - | - | 98 |
| 58 | Condensate of VV1 from juice treatment | 2.4 | 115 | 2 | - | - | 98 |
| 59 | Sterilized must to juice treatment | 111.8 | 105.1 | 6 | 19 | - | 3404 |
| 60 | Sterilized must return to fermentation | 111.8 | 39 | 6 | 19 | - | 3371 |
| 61 | Alcoholic vapours – column D | 18.6 | 84.9 | 1.3 | - | 90 | 26521 |
| 62 | Return of alcoholic solution | 18.6 | 62.6 | 1.3 | - | 90 | 26511 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 63 | Condensate of vapour bleed CVV- to juice treatment | 27.1 | 110 | 1.7 | - | - | 93 |
| 64 | Condensate of vapour bleed CVV - to condensate tank | 27.1 | 82.2 | 1.7 | - | - | 70 |
| 65 | Vinasse to treated juice heating | 36.5 | 109.3 | 1.46 | | 0.02 | 412 |
| 66 | Vinasse return from treated juice heating | 36.5 | 98.6 | 1.46 | | 0.02 | 403 |
| 67 | Steam for juice treated heating | 0.5 | | | | | 668 |
| 68 | Condensate of juice treated heating | 0.5 | | | | | 111 |

Table 15: Flow description for Case $II_{TI}$ – Cogeneration type Configuration I

| | **Description** | **m (kg/s)** | **T (°C)** | **P (bar)** | **Brix** | **w %** | **ex** |
|---|---|---|---|---|---|---|---|
| 3 | Bagasse for cogeneration | 20.0 | 30 | 1 | 3 | - | 9979 |
| 20 | Vinasse (outlet distillation column A) | 52.9 | 109 | 1.46 | - | 0.004 | 576 |
| 32 | Water shortfall in condensate tank | -13.1 | 25 | 1 | | | 50 |
| 33 | Make up water for general uses | 145.3 | 25 | 1 | | | 50 |
| 35 | Vapour bleed V1 for heating use (total) | 8.7 | 116.1 | 1.69 | - | - | 616 |
| 36 | Steam for distillation column | 7.6 | 127 | 2.5 | - | - | 668 |
| 38 | Steam for dehydration column (extractive) | 1.6 | 159 | 6 | - | - | 796 |
| 39 | Steam for dehydration column (recovery) | 0.8 | 159 | 6 | - | - | 796 |
| 40 | Steam for juice concentration | 30.2 | 127 | 2.5 | - | - | 668 |
| 41 | Steam for must sterilization | 0.7 | 159 | 6 | - | - | 796 |
| 42 | Steam for sugar dryer | 0.2 | 127 | 2.5 | - | - | 668 |
| 44 | Steam for process (2.5 bar) | 41.4 | 127 | 2.5 | - | - | 668 |
| 45 | Steam bleed for process (6 bar) | 3.1 | 159 | 6 | - | - | 796 |
| 46 | Condensate of vapour bleeds (VV1) | 8.7 | 115 | 1.69 | - | - | 98 |
| 47 | Condensate of exhaust steam - Distillation column | 7.6 | 127 | 2.5 | - | - | 111 |
| 49 | Condensate of steam bleed - Dehydration column | 1.6 | 159 | 6 | - | - | 149 |
| 50 | Condensate of steam bleed - Recovery column | 0.8 | 159 | 6 | - | - | 149 |
| 51 | Condensate of exhaust steam - Juice concentration | 30.2 | 127 | 2.5 | - | - | 111 |
| 52 | Condensate of steam bleed - Must sterilization | 0.7 | 159 | 6 | - | - | 149 |
| 53 | Condensate of exhaust steam - Sugar dryer | 0.2 | 127 | 2.5 | - | - | 111 |
| 55 | Vapour condensates CVV (total) | 74.0 | 108.3 | 0.5 | - | - | 92 |
| 56 | Condensate (6 bar) | 3.1 | 159 | 6 | - | - | 149 |
| 57 | Condensate (2.5 bar) | 41.4 | 127 | 2.5 | - | - | 111 |
| 60 | Sulfur dioxide | 0.06 | 70 | 1 | | | 4892 |
| 61 | Steam generated at boiler | 42.2 | 530 | 100 | | | 1509 |
| 74 | Vapour bleed V1 for juice treatment | 1.9 | 116.1 | 1.69 | - | - | 616 |
| 75 | Condensate of vapour bleed V1 for juice treatment | 1.9 | 115 | 1.69 | - | - | 98 |
| 78 | Water for centrifugal washing | 2.4 | 25 | 1 | | | 50 |
| 79 | Water for dilution poor molasses | 0.3 | 25 | 1 | | | 50 |
| 80 | Water for dilution of sugar | 1.3 | 25 | 1 | | | 50 |
| 81 | Water added to pans | 0.4 | 25 | 1 | | | 50 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 82 | Steam for pre-heating of juice treated | 3.2 | 127 | 2.5 | - | - | 668 |
| 83 | Condensate of steam for pre-heating | 3.2 | 127 | 2.5 | - | - | 111 |
| 84 | Vapour bleed VV1 for REB-B | 5.1 | 116.1 | 1.69 | - | - | 616 |
| 85 | Condensate of vapour bleed VV1 for REB-B | 5.1 | 115 | 1.69 | - | - | 98 |
| 86 | Vapour bleed VV1 for REB-A | 1.8 | 116.1 | 1.69 | - | - | 616 |
| 87 | Condensate of vapour bleed VV1 for REB-A | 1.8 | 115 | 1.69 | - | - | 98 |
| 88 | Vapour bleed VV3 -vacuum pan | 14 | 97.6 | 0.93 | | | 525 |
| 89 | Condensate of vapour VV3 - vacuum pan | 14 | 97.6 | 0.93 | | | 82 |
| 94 | CVV outlet of juice treatment | 74.0 | 51.8 | 1.6 | | | 55 |
| 95 | Vinasse to juice treatment | 52.9 | 109.3 | 1.46 | | | 576 |
| 96 | Vinasse from juice treatment to distillation | 39.1 | 104.6 | 1.46 | | | 572 |
| 97 | Vinasse from distillation to juice treatment - return | 39.1 | 74.6 | 1.46 | | | 549 |
| 98 | Vinasse at outlet of juice treatment | 52.9 | 41.8 | 1.46 | | | 536 |
| 99 | Sterilized juice to juice treatment | 45.3 | 104 | 6 | 25.2 | - | 4451 |
| 100 | Sterilized juice from juice treatment | 45.3 | 54 | 6 | 25.2 | - | 4423 |
| 101 | Distillate AEHC to vacuum pans | 0.4 | 81.6 | 1.16 | | 93.5 | 27839 |
| 102 | Distillate AEHC from vacuum pans | 0.4 | 81.6 | 1.16 | | 93.5 | 27778 |

From figures 10 and 11, it can be noticed that to achieve reductions in steam consumption, as well as in water usage, the heat exchanger network became more complex and expensive, owing to the temperature differences in heat exchangers which are lower in comparison to no integrated cases, which results in larger areas of heat exchange. Moreover, depending on the lay-out and the operational conditions sometimes the target of minimum energy requirements cannot be achieved. Thus, for Case $II_{TI}$ the hot utility consumption achieved was 15% higher (149.1 t/h) in comparison to the respective target.

Finally exergy balances in each subsystem assumed were done in order to calculate the rate of irreversibility generation. These values are presented in Table 16

Table 16: Rate of Irreversibility generation (kWh/t cana)

| **Subsystem** | **Case I** | **Case II** | **Case $I_{TI}$** | **Case $II_{TI}$** |
|---|---|---|---|---|
| I. Extraction system | 98 | 98 | 98 | 98 |
| II. Juice treatment | 42 | 15 | 33 | 9 |
| III. Juice concentration | 4 | 43 | 4 | 45 |
| IV. Crystallization | - | 18 | - | 15 |
| V. Fermentation and Sterilization | 136 | 109 | 123 | 104 |
| VI. Distillation | 30 | 7 | 15 | 6 |
| VII. Dehydration | 5 | 3 | 5 | 3 |

| | | | | |
|---|---|---|---|---|
| VIII. Cogeneration | 437 | 472 | 311 | 263 |
| IX. Condensate tank | 2 | 6 | 2 | 1 |
| X. Water treatment system | 1 | 1 | 1 | 1 |
| **Total** | **610** | **772** | **591** | **545** |

It can be observed that, for all cases, the subsystem with the most irreversibility generation is the cogeneration system. Other subsystems with significant irreversibility generation are the fermentation and sterilization, the extraction system and the juice treatment. Regarding the cogeneration and the fermentation process their irreversibilities are high because of the chemical and biochemical reactions happening. On the other hand, the extraction system presents a significant consumption of mechanical energy at mills. Regarding the no integrated cases the irreversibility in Case II was higher than Case I, however for integrated cases, irreversibility of Case $II_{TI}$ was lower. Finally, it can be said that heat integration promoted a reduction of irreversibility generation of 3.2% for the autonomous distillery (Case I) and 29% for the combined sugar and ethanol production plant, which shows that Case II has a higher potential to improvements.

## 5 Conclusion

This study showed the potential reduction in steam consumption and in the effective water collecting requirement resulting from heat integration. Through the target calculation, it was observed that the reduction in steam consumption was 34% and 37% for cases I and II respectively, it leads to a significant increase in the bagasse surplus when backpressure steam turbines are adopted in cogeneration system or the electricity surplus when condensing extracting turbines are adopted. These results show that both cases have a similar potential with respect to the economy in steam consumption, however, achieving the targets of minimum energy requirements in Case II shows to be more difficult owing to the complexity and the cost of the heat exchanger network. Regarding the water usage, cases without heat integration I and II already have water recycling and reuse, thus this study shows further savings of water use owing to heat integration. The reductions in effective water collecting were 24% and 13% for cases I and II respectively in comparison with cases without heat integration. It happens because in Case I much of the water consumption is for cooling purposes. Regarding the exergy analysis, it showed that Case II has the greatest potential for irreversibility reduction because of the significant irreversibility reduction in cogeneration system. Another interesting observation is the significant reduction of irreversibility in the juice treatment system because of the utilization of process streams instead of vapour of first effect.

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