



Graphical Analysis of Plant-Wide Heat Cascade for Increasing Energy Efficiency in the Production of Ethanol and Sugar from Sugarcane

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Abstract

Increased energy efficiency in the production of renewable energies can contribute to sustainable economic growth, with less consumption of fossil resources, less greenhouse gas emissions, and more energy supply certainty. The most abundant bio-based fuel for automobile transportation is presently ethanol. Brazil is an important producer of ethanol and uses sucrose from sugarcane, which is currently the most efficient feedstock for bioethanol production. The improvement of ethanol production in existing plants by heat integration can lead to a significant increase in energy efficiency. This paper presents diagrams in which data necessary for heat integration are organized in a new way. For the first time, the entire heat cascade through the individual components of ethanol and sugar production is analyzed, including the boiler, steam turbine, heat exchangers, and process operations. In autonomous plants, the produced ethanol and electricity correspond to about 35 and 8% of the inlet energy, respectively; in combined ethanol-sugar plants, the produced ethanol, sugar, and electricity correspond to about 16, 22, and 9% of the inlet energy, respectively. The remaining energy (53–57%) leaves the plant as residues or is rejected to the ambient as heat. Opportunities for increasing the plant energy efficiency by modifying the process operations, heat exchangers, turbine system, and boiler are identified and discussed. The analysis of the plant-wide heat cascade makes it possible to understand the relation between the combustion energy in a boiler, the exergy of combustion gases and high-pressure steam, the production of electricity through a turbine, and the thermal energy consumption in heat exchangers and process operations. This holistic perspective helps improve the energy performance in the production of ethanol and sugar.

Keywords Exergy · Heat integration · Pinch analysis · Boiler · Turbine · Heat exchanger

Highlights • Boiler-turbine-process ETD for improving energy integration in production plants

- Flow rate of cascaded heat through each component of ethanol and sugar production
- Graphical relation between electricity production and heat consumption
- Analysis of exergy decrease through boiler, turbine, and process

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Introduction

Today's research community is focusing on solutions for a future world with less consumption of fossil resources, less greenhouse gas emissions, and more certainty in energy supply in a context of rising demand for power, heat, and transportation fuels. Increasing energy and resource efficiency and developing renewable energies, including biomass, can contribute to sustainable economic growth. The most abundant bio-based fuel for automobile transportation is presently ethanol. Bio-based ethanol is produced from fermentation of sugars obtained from biomass feedstock, which usually contains sucrose (e.g., sugarcane, sugar beet) or starch (e.g., corn, wheat). Corn and sugarcane are the feedstocks used in the USA and in Brazil, respectively, which are the largest ethanol producers in the world. It has been shown that sugarcane is the most efficient resource for producing bioethanol (Dias Marina et al. 2009). An important by-product generated during

sugarcane processing is bagasse, which is usually burned in a boiler for the production of steam and electrical energy, providing the energy necessary to fulfill the process requirements. The improvement of the ethanol production process makes it possible to produce surplus bagasse, which can be used as a fuel source for electricity generation or as raw material for producing chemicals. Heat integration of the ethanol production process in existing plants can lead to a significant increase in energy efficiency (Pina et al. 2017).

In heat integration applications, graphical methods are widely used since they provide a good overview of the often complex energy systems of manufacturing process industries. The most widely used and best known of the insight-based graphical heat integration methods is pinch analysis. The representation of process heat sources and demands with hot, cold, and grand composite curves, which are cumulative heat load curves as a function of temperature, has contributed to the success of pinch analysis for designing the heat exchanger network (HEN), the utility system, and for modifying process operations. According to its base principle, a pinch temperature separates a heat-deficit region (above the pinch) and a heat excess region (below the pinch). In order to reduce energy consumption, heat transfers from the heat-deficit region to the heat excess region should be avoided. Hot and cold composite curves provide useful information for HEN design (Linnhoff and Hindmarsh 1983), while the grand composite curve provides indications about the optimal utility system (Maréchal and Kalitventzeff 1996, 1999). The plus/minus principle, in the context of pinch analysis, was developed to identify process modifications leading to energy savings. It states that, above a pinch, the amount of heat provided by heat sources should be increased or the amount of heat required by heat demands should be decreased. Conversely, below a pinch, the amount of heat required by demands should be increased or the heat provided by sources should be decreased. This principle has been used to identify opportunities for heat integration using specific equipment such as distillation columns (Linnhoff et al. 1983), evaporators (Smith and Linnhoff 1988), heat pumps (Linnhoff and Townsend 1982), and heat engines (Berntsson et al. 2013).

The energy transfer diagram (ETD) was recently developed to improve energy efficiency in industrial systems. This diagram and its associated concepts make it possible to visualize the principles of conservation and degradation of thermal energy in an industrial plant. The ETD represents the flow rate of cascaded heat as a function of temperature through each utility component, process operation, and heat exchanger. This diagram facilitates the identification of modifications that improve the overall energy efficiency of a plant, for the reason that reducing the thermal energy consumption in a process implies reducing the flow rate of cascaded heat from the heating utility to the ambient through the operations or the heat exchangers. Pinch analysis is a powerful and widely used method for

process integration in industrial practice, owing to its graphical representation and the simplicity of its concepts. Nonetheless, it does not provide information about the heat cascade through individual heat exchangers or process operations, such as distillation columns or reactors. Consequently, it does not explain the presence of a pinch in the HEN, which results from heat cascade through the process operations. This cascade corresponds to the empty region at the right of the grand composite curve and is represented in detail in the ETD. Also, the heat cascade through the heat exchangers, which corresponds to the empty part at the left of the grand composite curve, is represented in detail in the ETD. The links between the composite curves of pinch analysis and the ETD were described in previous papers (Bonhivers et al. 2015, 2016). In summary, the ETD is a map, a graphical aid that includes the composite curves of pinch analysis, shows how these are connected through the individual components of an industrial process, and helps identify solutions for reducing the flow rate of cascaded heat in order to increase energy efficiency.

In several studies, pinch analysis was applied to improve the energy efficiency of ethanol production. The method was used to improve the HEN (Lopez-Castrillon et al. 2018) or to better integrate distillation columns (de Souza Dias et al. 2011), which are the main heat consumers in ethanol plants (Ensinas 2008). However, the heat cascade through the plant components has not been analyzed. The objective of this paper is to present the analysis results of energy integration through the perspective of the site-wide heat cascade through all individual components of an ethanol plant, including boiler, steam turbine, heat exchangers, and process operations. The paper also presents several diagrams in which data necessary for heat integration are gathered and arranged in a new way to provide a holistic perspective on the energy system. First-generation ethanol, based on the fermentation of sucrose from sugarcane, is produced either in “autonomous ethanol plants” or in “combined ethanol-sugar plants.” To identify and analyze energy opportunities, models of sugarcane-based ethanol processes, the boiler, and steam turbines are developed. Then, process integration methods are used to increase the energy performance, including pinch analysis, exergy analysis, and heat cascade analysis with the ETD. The first section of this paper describes the process operations in autonomous ethanol plants and ethanol-sugar plants. The second section summarizes the concepts of heat cascade analysis. The third section presents new diagrams for plant-wide energy integration and the analysis results for autonomous ethanol production, including the successive studies of the process operations, heat exchanger network, steam turbine, and boiler. The fourth section presents the analysis results for combined ethanol and sugar production. The last section includes an evaluation of solutions to increase the energy performance in ethanol plants and a discussion of how the data necessary for heat integration are gathered and organized in the diagrams.

Description of Process Operations

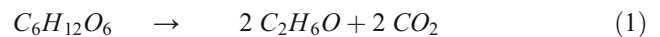
We considered a production plant that produces sugar and/or ethanol 200 days a year and receives 500 t/h of sugarcane, which typically contains water (71 wt.%), sucrose (14 wt.%), and fiber (13 wt.%) composed of cellulose, hemicellulose and lignin, and impurities and dirt (2 wt.%).

First-Generation Autonomous Ethanol Plants

In the first-generation process, sucrose from sugarcane is used as raw material to produce ethanol. The process includes the following main steps to produce 1000 m³ of anhydrous ethanol daily: cleaning of the sugarcane, extraction of sugars by milling, juice treatment and concentration, fermentation, and product purification by distillation (Fig. 1).

In the first step of the process, dirt is removed using a dry-cleaning system. Sugar is extracted through mills that use water to enhance recovery. Mills produce sugarcane bagasse (50 wt.% moisture content) and juice. Bagasse is burned in a boiler to generate HP steam (about 90 bars), which is then expanded through a turbine to produce electricity and lower pressure steam (between 2 and 10 bars) for the process. The

sugarcane juice is submitted to physical and chemical treatments to enhance impurities removal, such as minerals, salts, acids, and fiber. Screens and hydro-cyclones are used in the physical treatment. In the chemical treatment, phosphoric acid is added to improve impurities removal during settlement by clarification in a following step, and then the juice is heated from 30 to 70 °C. Preheated juice receives lime, is mixed with the recycled filtrate obtained at the cake filter, and is heated up to 105 °C. Hot juice is subsequently flashed to remove air bubbles and sent to a clarifier. The produced mud contains calcium phosphate, which is a precipitate resulting from a reaction between lime and phosphoric acid. During settlement, the mud drags other impurities contained in the juice. The mud is filtered to recover the sucrose. The filtrate is then recycled to the juice before the second heating operation, while the filter cake is used as fertilizer in fields. Clarified juice, which contains around 15 wt.% diluted solids, is subsequently concentrated to 22% before fermentation to reduce the energy consumption in the product purification step. The juice is concentrated either through a 5-effect evaporator or in a single-effect evaporator. In a single-effect evaporator system, the juice is concentrated in only one step. Consequently, it is not necessary to use the vapor produced in this operation for other stages to further concentrate the juice; the vapor produced at this single step can be used for other heat demands. In the 5-effect evaporator, part of the juice is concentrated to 65 wt.% sucrose and then mixed with the remaining juice to yield 22% weight sucrose. The resulting juice is cooled to 35 °C before fermentation. The fermentation reactor receives the concentrated juice and a yeast suspension containing about 28% yeast cells (vol.). In the fermentation step, fructose and glucose are mainly converted into ethanol and carbon dioxide, as represented in Eq. (1):



The fermentation reaction is slightly exothermic. As the fermentation temperature is critical to the yeast activity, the reactor has to be maintained at 30–35 °C by cooling. The fermentation gas is sent to an absorber column to recover ethanol, while the liquid product of fermentation is centrifuged to recover yeast cells. After centrifugation, the liquid is mixed with the alcohol solution from the absorber, preheated from 35 to 90 °C, and sent to the distillation section, which usually comprises four columns in Brazil. The preheated fermentation product, containing around 10 wt.% of ethanol, is sent to a beer column at atmospheric pressure that produces second-grade ethanol at the top, stillage containing around 97 wt.% water at the bottom, and liquid and vapor phlegm containing 40–50 wt.% ethanol as side streams. The stillage can be concentrated with a multiple-effect evaporator, and the concentrate can be burned in a boiler or recycled to fields as fertilizers. The vapor and liquid phlegm streams are

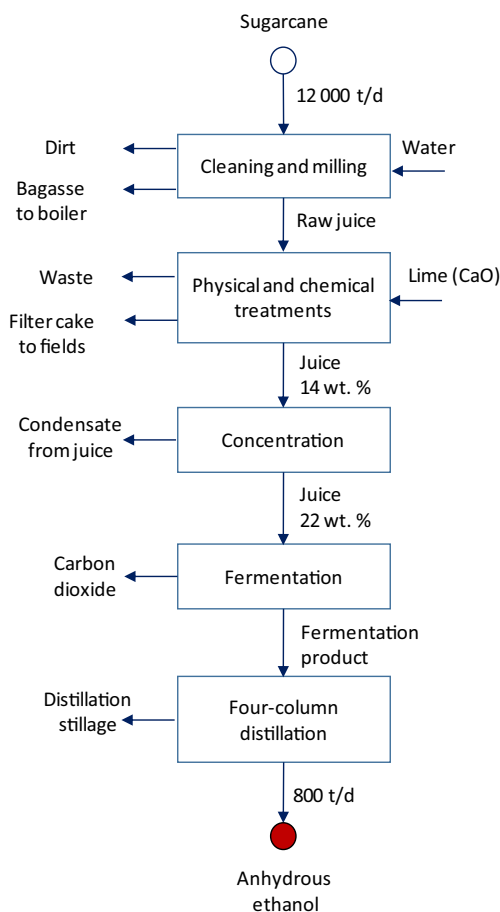


Fig. 1 Main operations in the first-generation ethanol process

sent to a rectification column at atmospheric pressure. Hydrous ethanol containing around 93 wt.% is produced at the top of this second column and stillage at the bottom. Extractive distillation with ethylene glycol as solvent makes it possible to obtain anhydrous ethanol (99.5 wt.%). Ethylene glycol is fed near the top of the extraction column, and ethanol containing around 7 wt.% of water is fed near the bottom. The column produces anhydrous ethanol and a mixture containing glycol, water, and ethanol traces. A recovery column, which operates at low pressure (20 kPa), is used to purify this mixture. Pure ethylene glycol is obtained at the bottom and is then cooled and recycled to the extraction column; the top product contains water and ethanol and is recycled to the beer column (Efe et al. 2007).

Ethanol-Sugar Plants

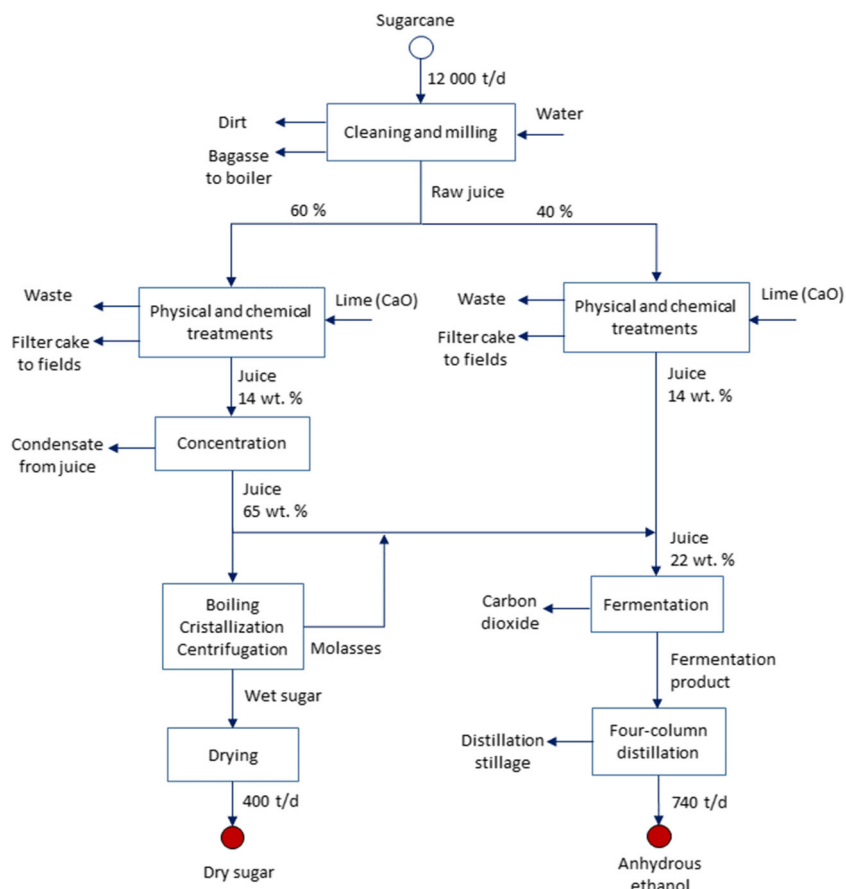
In the combined production of ethanol and sugar, the juice produced by milling is divided into two parts: 40% is sent to the ethanol line and 60% to the sugar line. The sugar production line includes the physical and chemical treatment of the juice, its concentration, crystallization and centrifugation, and finally the sugar drying (Fig. 2). The physical and chemical treatment for sugar production includes the same steps as for ethanol production. Nevertheless, more lime (CaO) is used in

comparison with the ethanol plant. Sulfur dioxide (SO₂) is used to reduce the color of the juice in the production of white sugar. After clarification, the juice is concentrated from around 15 to 65 wt.% soluble solids content in multiple-effect evaporators, usually consisting of 5 evaporation steps. Before sucrose crystallization, vacuum pans are used to evaporate more water from the concentrated juice. After a certain residence time, the mixture of sugar crystals and syrup is transferred to the crystallizers where sucrose is allowed to crystallize before centrifuging. The mixture in the crystallizers is sent to centrifuges to separate crystal from the mother liquor, where hot water and steam are used to wash the crystals. Continuous basket centrifuges produce molasses, which is sent to alcoholic fermentation, and sugar. Finally, sugar obtained in the centrifuges is dried in a rotary drum drier in which its moisture is reduced to around 1.0% and cooled (de Souza Dias et al. 2015).

Concepts for Analyzing the Heat Cascade Through a Process

In this paper, process heat demands and process heat sources correspond to cold and hot streams in the terminology of pinch analysis, respectively. We considered that a process is

Fig. 2 Main operations in the ethanol-sugar process



composed of process operations and HEN. A production plant may include a boiler, a turbine, and a process. Heat at a greater temperature than ambient can be transferred to the ambient, which corresponds to maximum entropy. As heat is cascaded through a system (e.g., process operation, heat exchanger, or plant section), the cumulative heat content curve of the outlet is located at lower temperature in comparison with the cumulative heat content curve of the inlet. The final and maximum values of the two cumulative heat content curves are the same, which results from energy conservation; however, the heat cascade leads to an increase of thermal energy located at lower temperature, which results from entropy increase. The difference between the two cumulative curves is equal to the flow rate of cascaded heat through the system as a function of temperature. More detail and examples can be found in Figs. 3, 4, and 6 in Bonhivers et al. 2014. The ETD is

composed of regions that, in this paper, are termed energy transfer region (ETR) corresponding to a system, which can be any plant component, e.g., a unit operation or a process section.

The ETR of a system shows the flow rate of cascaded energy through the system as a function of temperature T ; it is equal to the difference between the sum of the enthalpy rates of the outlets and the sum of the enthalpy rates of the inlets at temperature T , with the ambient temperature as the reference (Eq. 2).

$$ETR_{system}(T) = \sum_{out=1}^{Outlets} \dot{H}_{out}(T) - \sum_{in=1}^{Inlets} \dot{H}_{in}(T) \quad (2)$$

The ETR can equivalently be expressed by the following energy balance. Heat cascaded from temperature T is equal to heat cascaded from $T + 1$ plus the heat inlet between T and

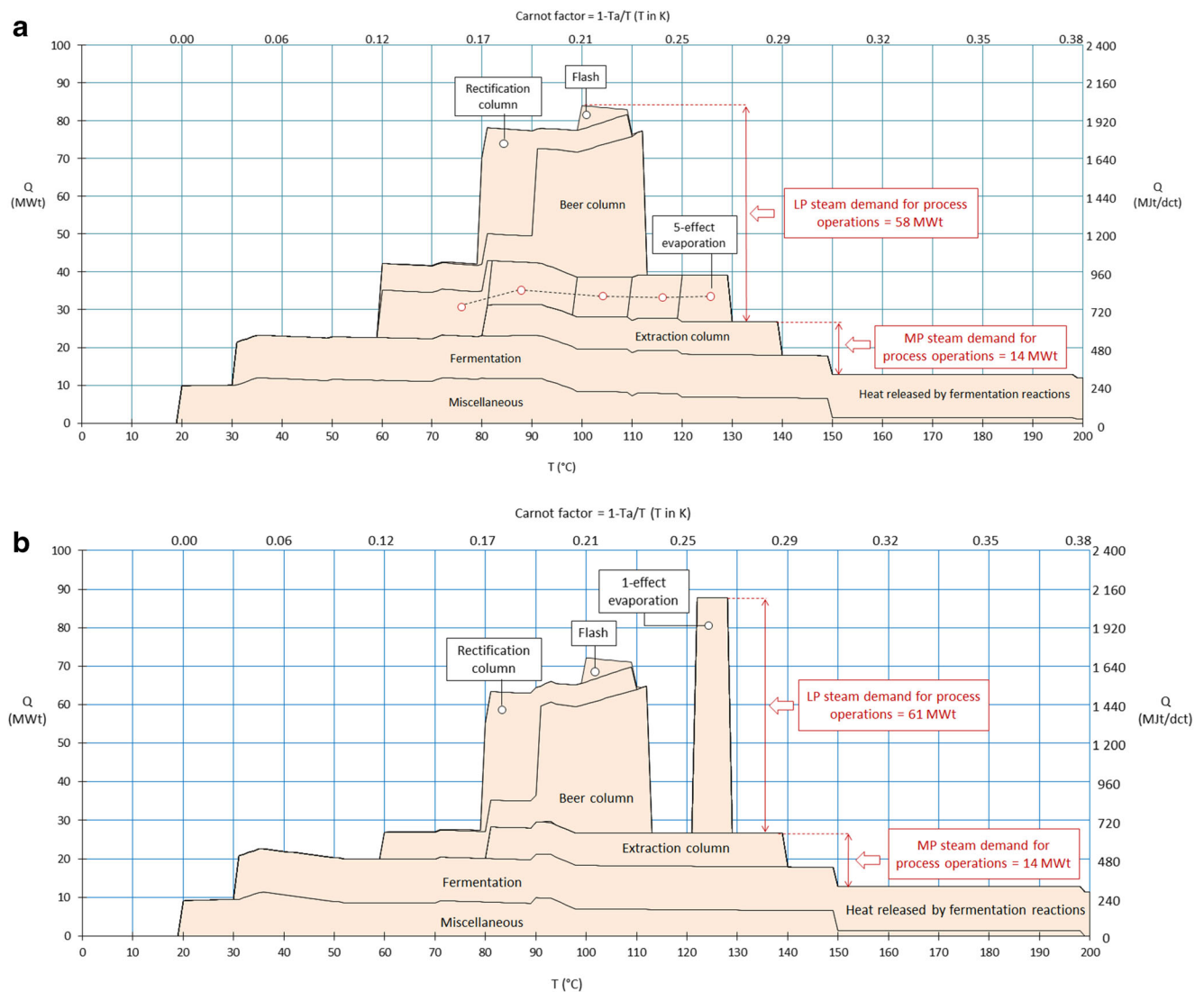


Fig. 3 Ethanol plant: ETD of process operations. **a** ETD of process operations with a 1-effect evaporation system. **b** ETD of process operations with a 5-effect evaporation system

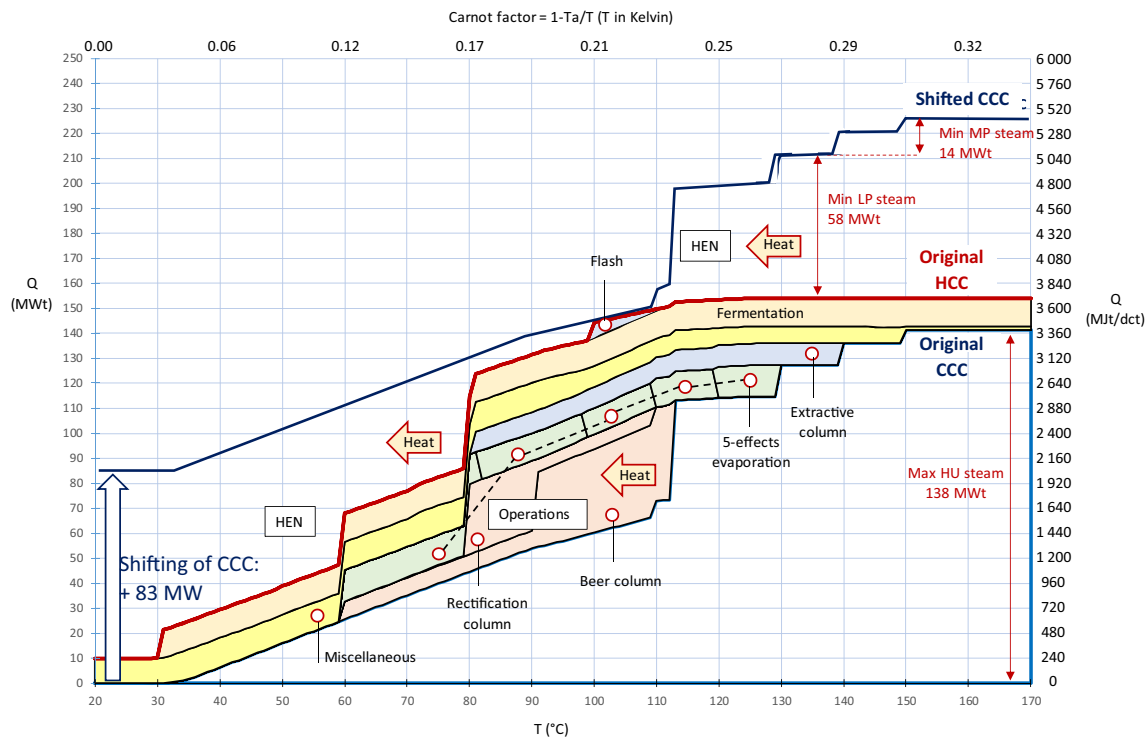


Fig. 4 Ethanol plant—link between the CCC, the HCC, and the heat cascade through process operations

$T + 1$ minus the heat outlet between T and $T + 1$ (Eq. 3).

$$ETR_{system}(T) = ETR_{system}(T + 1) + \sum_{in=1}^{Inlets} FCP_{in}(T) - \sum_{out=1}^{Outlets} FCP_{out}(T) \quad (3)$$

This relation is valid for any system, e.g., an operation, a heat exchanger, or an entire process. If the system in question is a particular heat exchanger HE_i , the corresponding ETR can also be expressed as the difference between the cumulative load curve of the sink and the cumulative load curve of the source (Eq. 4). In the terminology of pinch analysis, the ETR of a heat exchanger is equivalently expressed as the difference between the load curve of the cold stream and the load curve of the hot stream. The ETR of a heat exchanger represents the flow rate of cascaded heat through the exchanger as a function of temperature T (Eq. 5). The ETR of all existing exchangers represents the total flow rate cascaded heat through the HEN as a function of temperature T (Eq. 6).

$$ETR_{HEi}(T) = \text{load curve of sink}_{HEi}(T) - \text{load curve of source}_{HEi}(T) \quad (4)$$

$$ETR_{HEi}(T) = ETR_{HEi}(T + 1) + FCP_{HEi}^{source}(T) - FCP_{HEi}^{sink}(T) \quad (5)$$

$$ETR_{HEN}(T) = \sum_{HEi=1}^{Exchangers} ETR_{HEi}(T) \quad (6)$$

Heat is cascaded from a heating utility to the ambient through heaters, process-process heat exchangers, coolers, and process operations in the following way. In the first step, heat from a heating utility is cascaded through heaters to some process heat demands (PDs). In the second step, heated PDs are used in process operations, i.e., heat from process operation inlets is cascaded through process operations to outlets. Consequently, outlet streams from process operations can serve as process heat sources (PSs). In the third step, heat from PSs is cascaded either through coolers to the ambient or through process-process exchangers to other PDs, which then will enter process operations (back to second step). Therefore, the difference between the hot composite curve (HCC), which is the cumulative load of process operations outlets, and the cold composite curve (CCC), which is the cumulative load of process operations inlets, is equal to the flow rate of cascaded heat through the process operations. Moreover, the difference between the balanced CCC (cumulative load of HEN outlets, composed of the cooling utilities and PDs) and the balanced HCC (cumulative load of HEN inlets, composed of the heating utilities and PSs) is equal to the flow rate of cascaded heat through the HEN. Examples are presented in the next sections (Figs. 4, 5, 9, and 13). In the ETD, all individual ETRs are stacked. Unless the heat is converted into another form of energy, the sum of all flow rates of cascaded heat as a function of temperature is constant when considering the total heat cascade from the heating utility to the ambient. Therefore,

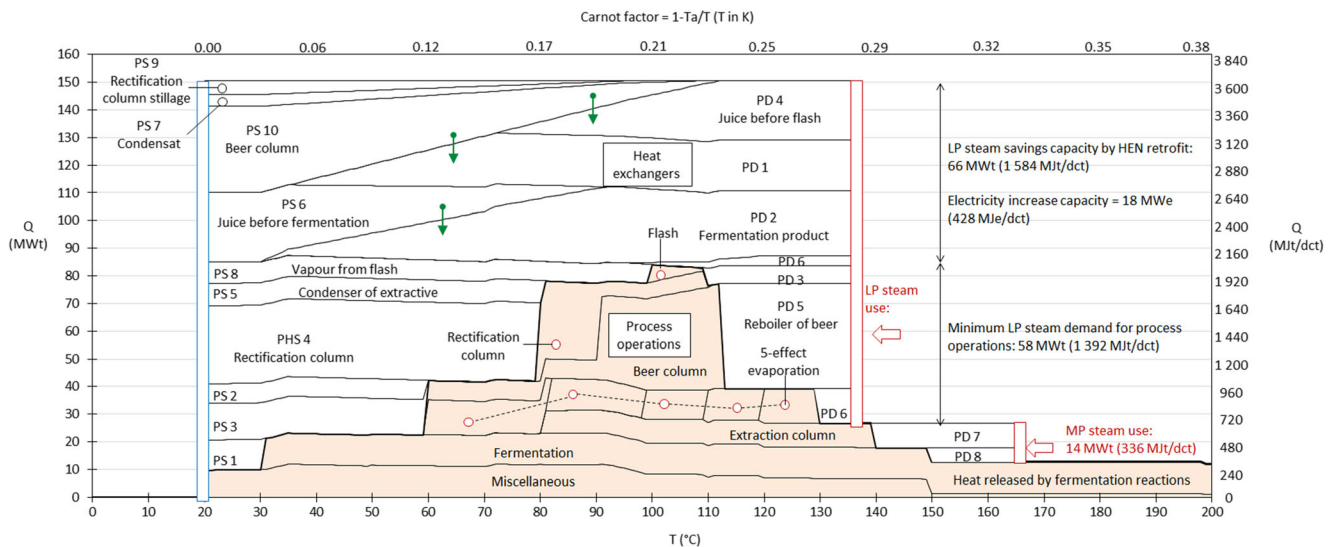


Fig. 5 Ethanol plant—ETD of process operations and HEN with maximum energy consumption

any reduction in heating utility consumption through a process implies a set of modifications that decrease the flow rate of cascaded heat through the HEN and process operations in the entire temperature interval from the heating utility to the ambient (Bonhivers et al. 2015).

The exergy of a stream is the theoretical potential for producing mechanical or electrical energy, which implies isentropic conversion. The area of an ETR plotted as a function of the Carnot factor is equal to the reduction of the exergy through the system. As heat above ambient temperature can be transferred until the ambient, the area between (1) the ambient temperature level and (2) the cumulative heat content curve of a stream as a function of the Carnot factor is equal to its total exergy. The principle of entropy increase is equivalent to the principle of exergy decrease: the total exergy at the outlet of any system is always smaller than or equal to the total exergy at the inlet. This results from the second law of thermodynamics, which states that the total entropy of an isolated system does not decrease. Consequently, the exergy of the steam produced by a boiler heat exchanger and entering a turbine is always greater than or equal to the produced mechanical work plus the exergy of the steam at the outlet, which can be either used as heating utility to a process or directly condensed with a cooling utility. In this paper, the ETD uses this information to organize data helpful to plant-wide energy analysis.

Analysis of Plant-Wide Heat Cascade in the Autonomous Ethanol Production

In this section, using several proposed diagrams, we explain the entire heat cascade and present the results of three analyses that provide solutions for increasing the energy performance of autonomous ethanol plants. With the process ETD, we

discuss modifications in process operations and heat exchangers and their impact on energy consumption. We also present the boiler-turbine process ETD, which gathers data in a new way to evaluate the impact of the fuel composition, steam turbine parameters, and process heat consumption on the production of electricity.

Analysis of the Process Operations, Ethanol Plant

In Fig. 3a, each ETR represents the flow rate of cascaded heat through a system as a function of temperature. The ETR of a system, which corresponds here to an operation in the ethanol process, is equal to the difference between the outlet and inlet enthalpy curves. The temperature in degrees Celsius is shown at the bottom of the diagram, while the corresponding Carnot factor $1 - T_a/T$, where T and T_a represent temperature and ambient temperature in Kelvin, respectively, is shown on the top horizontal axis. Heat enters at the right and leaves at the left of ETRs. As an example, the ETR of the extractive distillation column shows that heat enters at 137 °C at the reboiler, is degraded through successive column stages, and leaves at 80 °C at the condenser. Figure 3a shows that the main operations that degrade heat are the following: the distillation through the beer, rectification and extraction columns, the 5-effect evaporation system, the fermentation, and the juice flashing. The ETR named “Miscellaneous” gathers all operations with a low flow rate of cascaded heat, such as the distillation through the ethylene glycol extraction column, non-isothermal mixings, the cooling of mass outlets to ambient temperature, and heat losses from equipment.

The fermentation reactions are slightly exothermic, releasing 250 MJ per dry cane ton (dct). This heat has to be removed from the reactors in order to maintain the yeast activity, which is optimal around 30–35 °C. The ETR corresponding to the

fermentation considers the enthalpy of reaction, as the composition changes from the inlet to the outlet. The reaction products are mainly ethanol and carbon dioxide, while the reactants include glucose and fructose (Efe et al. 2007). As shown in Fig. 3a, the entire set of process operations, including the 5-effect evaporation system, requires 14 MWt (336 MJt/dct) of MP steam at 165 °C and 58 MWt (1392 MJt/dct) of LP steam at 135 °C.

It is worthwhile noting that the ETR corresponding to the fermentation process, shown in Fig. 3a, has an annotation at its higher temperature extremity indicating “heat released by fermentation reactions.” On the ETD, any process operation that involves the release of heat through an exothermic reaction is diagrammatically represented on its ETR as having an equivalent quantity of energy cascaded down from higher temperature. This energy, appearing on the right hand side of the heat cascade, is the energy stored in chemical bonds that will be released at lower temperature through exothermic reaction. In Eq. 2, enthalpy includes energy necessary to heat the inlets and outlets from the ambient to their actual temperatures and energy stored in chemical bonds. Chemical enthalpy corresponds to a step at high temperature in enthalpy curves, $H(T)$. If there is no reaction in the operation, then the difference between outlet and inlet chemical enthalpy is equal to zero. However, if an exothermic reaction occurs, this difference is positive and is represented on the ETR as arriving from higher temperature.

The ETRs of the beer and rectification columns show that these have an important impact on the degradation of heat through the overall cascade and on energy consumption. These columns are connected. Heat enters the beer column at 110 °C through the reboiler, degrades through the distillation stages, and leaves at 90 °C with the vapor “phlegm” for the most part, with a smaller part at the condenser level. Heat enters the rectification column at 108 °C through the reboiler and at 90 °C with the vapor phlegm from the beer column. This heat is degraded through distillation stages and leaves at the condenser at 80 °C. As a summary, a large part of heat enters at 110 °C in the beer column, is transferred through the phlegm at 90 °C from the beer column to the rectification column, and goes out at the condenser of the rectification column at 80 °C. To reduce the energy consumption, it is possible to reduce the pressure in the beer column such that its reboiler could be heated with the rectification column condenser (i.e., sliding the beer column ETR to the left of the rectification column ETR in Fig. 3a). The resulting vapor phlegm at the outlet of the beer column would then be compressed before being sent to the rectification column (de Souza Dias et al. 2011). The exergy change through a system is equal to the surface area of the corresponding ETR represented as a function of the Carnot factor, which is shown in Fig. 3a. Therefore, the amount of necessary mechanical work for compressing the phlegm can be evaluated by the ETR

resulting from the difference between the Carnot factor after and before compressing (Bonhivers et al. 2015). The figure also shows that the extractive distillation has a significant impact on the minimum thermal energy consumption required by the process. To produce with less energy anhydrous ethanol from hydrous ethanol at the rectification column outlet, the extractive distillation column can be replaced by molecular sieves.

The ethanol process requires evaporating 550-kg water/dct to concentrate the sucrose content from 14 to 18 wt.% in the treated juice before fermentation. Evaporation of this amount of water requires roughly $550 \text{ kg/dct} \times 2.2 \text{ MJ/kg}$, or 1210 MJ/dct. This heat can be provided through one or several effects. In the 5-effect evaporation system, 242 MJ/dct ($1210 \div 5$) of heat is gradually cascaded from the first effect at 130 °C to the other effects, until the vapor outlet of the fifth effect at 60 °C. This multiple-effect evaporation system makes it possible to reduce the local energy consumption necessary for concentrating the juice. However, it requires significant investment cost, and the vapor outlet at the fifth effect at 60 °C can no longer be used. The corresponding heat cascade through the 5-effect evaporation system is visible on the ETD and crosses the maximum value of the total flow rate of cascaded heat through process operations, 83 MWt (1992 MJt/dct). From the perspective of pinch analysis, the operation of juice concentration crosses the maximum point (the “pinch”), which is located at 101 °C. It is worth mentioning that this localized understanding of the cause of the pinch phenomenon is not part of the current pinch method but is visible in the ETD. An alternative is replacing the 5-effect evaporation by a single-effect evaporation system; the latter is simpler and requires less investment. Although it implies much greater local heat consumption for the juice concentration, i.e., 1210 MJ/dct, the heat leaving the single effect can be efficiently reused in the process (Fig. 3b). If this heat is used for the reboilers of the beer and rectification columns, then the minimum LP steam consumption in the process operations would amount to 1464 MJt/dct (61 MWt). This solution results in only a small increase in LP steam consumption compared to the process with a 5-effect evaporation, which is 1392 MJt/dct (58 MWt). Moreover, the excess energy (16 MWt, or 384 MJt/dct) at the outlet of the single effect could be used inside the process to simplify the HEN, or exported to another process.

Analysis of the Heat Exchanger Network, Ethanol Plant

Table 1 presents the process heat demands (PD) and process heat sources (PS) for the ethanol plant with a 5-effect evaporation system. A minimum individual temperature difference, $\min \Delta T$, is presented for each stream in the rightmost column. This represents the stream-specific contribution to a minimum temperature difference through a transfer. The use of $\min \Delta T$

Table 1 Autonomous ethanol plant—data extracted for HEN design

ID	Description	Q (MWt)	Q (MJt/ tdc)	T_c (°C)	T_h (°C)	$Min\ I\Delta T$ (°C)
Process heat demands						
PD1	Juice before liming	19.9	478	35	70	5
PD2	Fermentation product before beer column	21.2	510	31	90	5
PD3	Reboiler of rectification column	6.2	149	108	109	5
PD4	Juice before flash tank	20.4	488	70	110	5
PD5	Reboiler of beer column	39.8	956	113	114	5
PD6	5-effect evaporator—evaporation at first effect	12.4	297	128	129	5
	5-effect evaporator—juice preheating	4.0	96	93	128	5
PD7	Reboiler of extraction column	8.8	212	139	140	5
PD8	Reboiler of recovery column	5.3	127	150	151	5
Total		138.1	3313			
Process heat sources						
PS1	Fermenters	8.8	212	30	31	5
PS2	Condenser of beer column	8.0	191	58	60	8
PS3	Vapor from the fifth effect of evaporator	13.3	319	60	62	8
PS4	Condenser of rectification column	28.3	680	78	80	8
PS5	Condenser of extraction column	8.8	212	78	80	8
PS6	Concentrated juice before fermentation	25.2	604	30	92	5
PS7	Condensates from 5-effect evaporator	5.8	138	50	95	5
PS8	Vapor from flash tank	4.5	108	100	102	8
PS9	Rectification column stillage	4.2	101	30	110	5
PS10	Beer column stillage	31.0	743	30	110	5
Total		137.8	3308			

ensures that the temperature difference in each exchanger respects the following condition (Eq. 7):

$$\Delta T_{d,s} \geq f_{\Delta T} * (\min I\Delta T_d + \min I\Delta T_s) \quad \forall d, s \quad (7)$$

With:

$\Delta T_{d,s}$ the temperature difference between demand d and source s

$f_{\Delta T}$ temperature difference factor

$\min I\Delta T$ minimum individual temperature difference

PD7 and PD8 require MP steam at 170 °C (Carnot factor = 0.35), while the other demands can be satisfied with LP steam at 135 °C (Carnot factor = 0.28). The heat demand PD6 for the first effect of the evaporation system is decomposed into two parts. The first part represents the juice preheating from 93 to 128 °C, while the second part represents the heat demand at 128 °C for evaporation in the first effect. PS7 refers to the cooling of vapor condensate coming from concentrating the juice through the 5-effect evaporation system. The maximum energy consumption of the process, i.e., without heat recovery through the HEN and without operation modification, is equal

to the total demand, i.e., 14 MWt (339 MJt/dct) of MP steam and 124 MWt (2974 MJt/dct) of LP steam.

Figure 4 shows the link between the heat cascade through the process operations and the cold composite curve (CCC) and the hot composite curve (HCC) of pinch analysis; these are the cumulative curves of the PD loads and PS loads as a function of temperature, respectively. As shown in Fig. 4, the HCC is equal to the CCC plus the flow rate of cascaded heat through the process operations. In other words, the energy provided by the heating utility is used to satisfy PDs; then these are used in operations; heat is cascaded through operations and leaves them as sources, which are the PSs. PDs after heating enter process operations, and PSs before cooling are process operation outlets. The CCC, after its shifting to just above the HCC, is also presented. The minimum energy requirement for the HEN results from the difference between the shifted CCC and the HCC. It is worth noting that the ETRs of the HEN can be located between the HCC and the shifted CCC (Bonhivers et al. 2016). An example is presented in the discussion section of this article (Fig. 13).

Figure 5 represents the heat cascade through the process operations and the HEN with maximum energy consumption.

It is assumed that all the heat from PSs is released to the ambient, at 20 °C. As can be seen, the total flow rate of cascaded heat as a function of temperature is constant from the MP and LP steam levels to ambient temperature. This results from the principles of energy conservation and entropy increase. The difference between the total energy consumption (138 MWt) in the process, which includes the operations and the HEN, and the maximum height of the process operations part (83 MWt) is equal to the capacity for thermal energy savings through HEN modifications. This thermal energy savings capacity, 66 MWt, corresponds to 18 MWe exergy savings. This value results from multiplying the capacity for LP steam savings (66 MWt) with the Carnot factor of LP steam (0.28), shown above the diagram, that is, $66 \text{ MWt} \times 0.28 = 18 \text{ MWe}$. These exergy savings can lead to an increase in electricity production. Table 2 presents the results of energy savings through HEN modifications. Energy savings depend on the temperature difference factor $f_{\Delta T}$. If the factor is equal to zero, then the theoretical maximum energy savings (66 MWt) is achieved. However, this condition requires an infinite heat exchanger surface area. If $f_{\Delta T}$ is increased to 1, 2, and 3, then the minimum temperature difference increases, the exchanger surface area decreases, and the investment costs are reduced. The pinch temperature corresponding to each factor $f_{\Delta T}$ and the electricity production increase corresponding to the thermal energy savings in the HEN are presented in Table 2. The maximum electricity production increase presented in the table, 15 MWe, is less than the value resulting from the capacity of thermal energy saving multiplied by the Carnot factor of the LP steam (0.28) shown in Fig. 5, 18 MWe, which assumes isentropic expansion. This difference is due to the isentropic efficiency of steam expansion through the condensing turbine, which is fixed at 85%.

The global guidelines to save energy through the HEN are the following (Fig. 5). Firstly, the heat content in the concentrated juice before fermentation (PS6, Table 1) and in the stillage coming from the distillation beer column (PS10) should be recovered. This energy should be used to heat the juice before the liming (PD1), the fermentation product entering the beer column (PD2), and the juice entering the flash tank (PD4). These saving opportunities can be identified with

pinch analysis, i.e., the composite curves of Fig. 4 show that process heat sources can satisfy process heat demands below the pinch. However, they can also be identified with the heat cascades through the HEN prior to heat recovery, as shown by the three downward arrows in Fig. 5: the large ETRs of PS6 and PS10 are well balanced with the large ETRs of PD1, PD2, and PD4 and overlap them. Figure 5 also shows other valuable heat sources: the condenser of the extraction column (PS5), the condenser of the rectification column (PS4), the condensate from the 5-effect evaporation system (PS7), the vapor from the flash tank (PS8), and the rectification column stillage (PS9). The heat transfer from these process sources to the juice before liming (PD1), the fermentation product before distillation in the beer column (PD2), and the juice before the flash tank (PD4) would result in reducing the total flow rate of cascaded heat through the HEN. In the ETD of Fig. 5, these modifications would lead to a corresponding reduction in the height of the top curve. Two HENs leading to heat savings are presented in the “Discussion” section (Figs. 12 and 14).

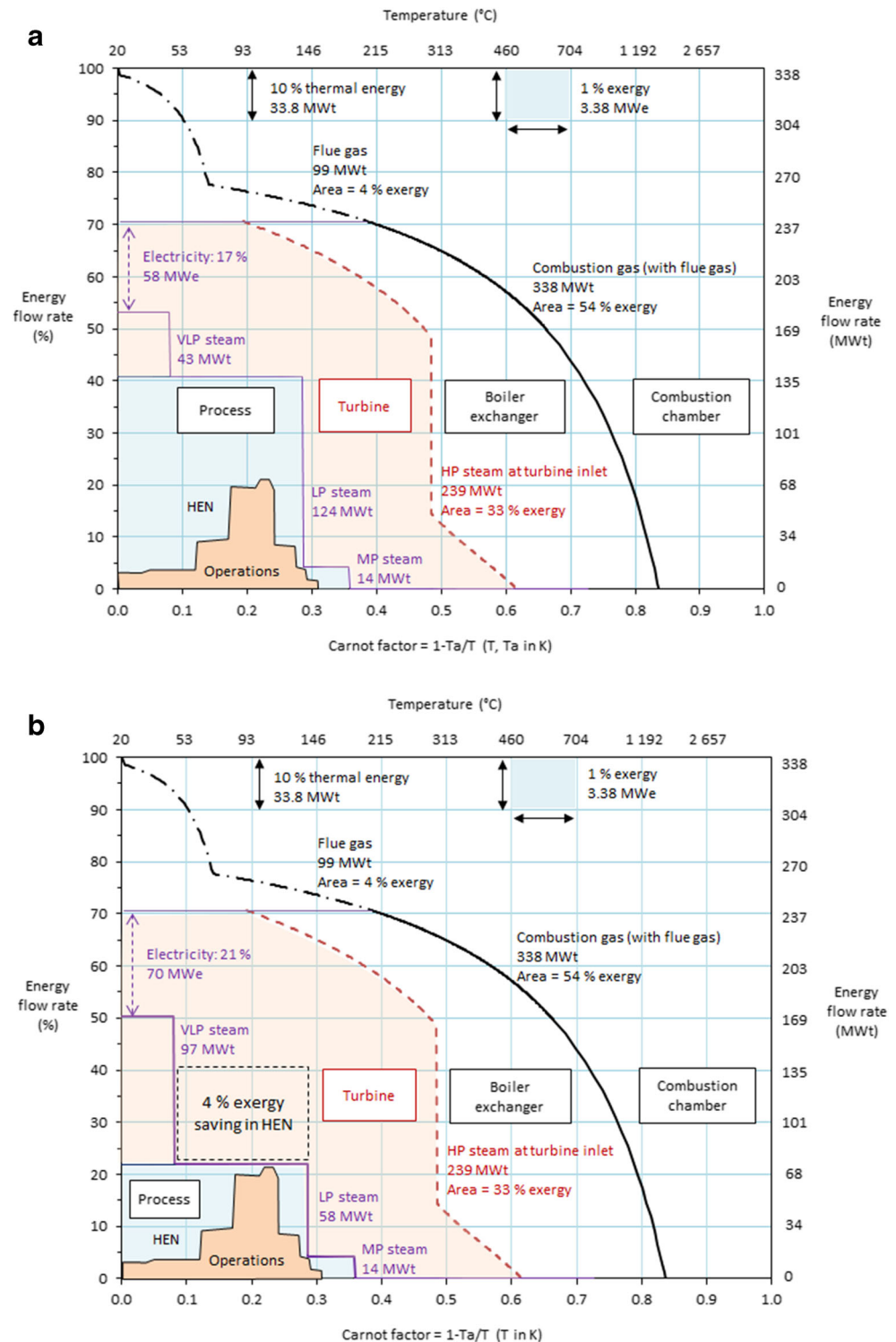
Analysis of the Entire Ethanol Plant: Boiler, Turbine, Process Operations, and HEN

The boiler-turbine-process ETD shown in Fig. 6a and 6b displays energy data in a new way to visualize the effects of the first and second laws of thermodynamics, i.e., energy conservation and degradation, at the industrial plant level. The diagram shows the progressive transfer of heat from right to left through the components of the plant as a function of the Carnot factor. It includes the bagasse combustion, the heat transfer through the boiler exchanger to produce high-pressure (HP) steam, the expansion of HP steam through a turbine with the production of electricity, and the heat cascade through the process (HEN and PO) with a 5-effect evaporation system. The heat cascade through individual process operations and heat exchangers was shown in detail in previous diagrams (Figs. 3, 4, and 5). The ETD of individual process operations of Fig. 3a is the detail of the lower part of the process region in Fig. 6a and 6b. The ETD of the process operations and heat exchangers together in Fig. 5 is the detail of the process region of Fig. 6a. The Carnot factor $1 - T_a/T$ is

Table 2 Autonomous ethanol plant—results of thermal energy savings

$f_{\Delta T}$ for heat recovery		0	1	2	3	Without heat recovery
Pinch temp.	°C	101	95	80	78	—
LP steam	MWt	58.7	65.9	76.9	87.7	123.8
Consumption	MJt/dct	1408	1581	1843	2102	2969
MP steam	MWt	14.1	14.1	14.1	14.1	14.1
Consumption	MJt/dct	340	340	340	340	340
Electricity prod. increase	MWe	15.1	13.4	10.9	8.4	0.0
	MJe/dct	362	322	261	201	0

Figs. 6 Ethanol plant: boiler-turbine-process ETD. **a** Boiler-turbine-process ETD: case with maximum energy consumption in the HEN. **b** Boiler-turbine-process ETD: case with minimum energy consumption in the HEN



shown on the horizontal axis below the diagram, while the corresponding temperature in degrees Celsius is shown at the top. The Carnot factor is zero at ambient temperature and one at infinite temperature. The vertical axis represents the energy flow rate, shown as percentage of the combustion enthalpy of the biofuel on the left and expressed in MW on the

right. Each curve represents the cumulative thermal energy content of a stream, starting from the Carnot factor equal to one. In Fig. 6a, the horizontal and the vertical axes are divided into 10 parts; therefore, each square inside the diagram represents 1% of exergy of the total resulting from the fuel combustion. Starting from the bagasse combustion at the right of

the diagram, the curve of the resulting combustion gas represents its cumulative thermal energy content. The produced combustion gas is sent to the boiler exchanger to produce HP steam. The resulting flue gas (dot-dashed line) leaves the plant at 200 °C; the change in the slope of the flue gas curve below 100 °C results from the vapor condensation at atmospheric pressure. The proportion of energy lost through the flue gas depends on its temperature and the bagasse composition, including its moisture. The HP steam curve is shown by the dashed red line and results from heating water from 90 to 510 °C at 90 bars, which implies vaporization at 303 °C, represented by the vertical section of the curve at this temperature. The boiler exchanger transfers heat to produce HP steam, corresponding to 33% of exergy (area at the left of the HP steam curve). This HP steam is sent to a turbine system to produce electricity and medium-pressure (MP) and low-pressure (LP) steams required for the process.

In Fig. 6a, the demand for MP and LP steams for the process corresponds to the maximum energy consumption in the HEN. Excess steam is expanded to very low-pressure (VLP) through a condensing turbine. It is assumed that the isentropic efficiency is equal to 85%. As the steam expansion is not isentropic, the exergy at the turbine outlet (electricity, MP, LP, and VLP steams) is less than at the inlet (HP steam). The amount of produced electricity through a steam turbine can be evaluated by Eq. 8:

$$W = \eta * (\text{Exergy of inlet steam} - \text{Exergy of outlet steams}) \quad (8)$$

With:

W produced electricity
 η isentropic efficiency

As shown on Fig. 6a, the exergy of the inlet and outlets steams are 33 and 13%, respectively. Consequently, the produced electricity is equal to 17%. The difference between the maximum height (71%) of the HP steam curve at the turbine inlet and the maximum height (54%) of the steam curve at the turbine outlet (MP, LP, and VLP) is equal to the amount of electricity (17%) produced by expansion through the turbine system.

In the ethanol plant, the bagasse with a moisture content of 50% coming from the milling is burned in a boiler. The combustion reactions occur at very high temperature and release 338 MWt of thermal energy, which corresponds to about 338 MWe as the quality factor of the fuel (ratio between energy and exergy) is close to one. In the boiler-turbine-process ETD, each internal square represents 1% exergy (3.38 MWe) of the total combustion. The combustion gas results from the heating of the air inlet with the energy released by bagasse oxidation and the change in its composition. The hot combustion gas is mainly composed of nitrogen, carbon dioxide, and

water and contains 100% of the thermal energy (338 MWt) and 54% of exergy (area at the left of the curve). This gas is sent to the boiler exchanger to produce HP steam. The combustion gas leaves the boiler exchanger at 200 °C; the resulting flue gas contains 29% of thermal energy (99 MWt) and 4% of exergy (area at the left of the flue gas curve). The produced HP steam contains 71% thermal energy (239 MWt) of the combustion total and 33% exergy, which corresponds to the number of internal squares at the left of the HP steam curve. It is possible to increase the exergy of HP steam by sliding the curve to the right, that is, by increasing its pressure or final temperature. The HP steam feeds the turbine system to produce electricity and MP and LP steams for the process. The heat from MP and LP steams is cascaded to ambient temperature through the operations and the HEN. The border between the operations and the heat exchangers is shown inside the process region. In Fig. 6a, we assumed that the maximal thermal energy consumption is required for the process, i.e., without heat recovery through the HEN. The process, with the 5-effect evaporation system and maximum energy consumption in the HEN, requires 14 MWt of MP steam and 124 MWt of LP steam. The heat cascade through the process, which includes the operation part (below) and the HEN part (above), leads to about 12% of exergy decrease (area of the process). Excess steam is expanded to VLP steam. The turbine produces 58 MWe of electricity (17% of the total combustion exergy). As a summary, the boiler-turbine-process ETD of Fig. 6a presents the flow rate of cascaded energy as a function of the Carnot factor through the boiler combustion chamber, the boiler exchanger, the turbine, and the process, which is composed of the HEN and operations. For comparison, Fig. 6b presents the situation with minimum energy consumption in the process, i.e., 14 and 58 MWt of MP and LP steams, respectively. The exergy saving (4%) in the process is shown by the area bordered by a dashed line. This exergy area corresponds to the gain in electricity production from 58 to 70 MWe. This increase in electricity production is less than in Table 2 since the VLP steam at the condensing turbine outlet still has some exergy ($T = 45$ °C, Carnot factor = 0.08) in Fig. 6a and 6b.

The diagram of Fig. 7 presents the plant-wide energy balance for the ethanol production. Energy inputs and outputs are shown at the right and the left of the diagram, respectively. Values are presented both as the percentage of total energy and in MW. Energy input, which amounts to 759 MW, is composed of combustion enthalpy of sugarcane (98.6%) and electricity (1.4%) used by some equipment; an important part of electricity consumption is used for the sugarcane milling. Electrical energy is transformed into mechanical energy, which is degraded through friction, and finally leaves the plant as heat. The combustion enthalpy of the rejects from cleaning and milling corresponds to 3.0% of the total inlet energy. At this step, bagasse, whose combustion energy amounts to

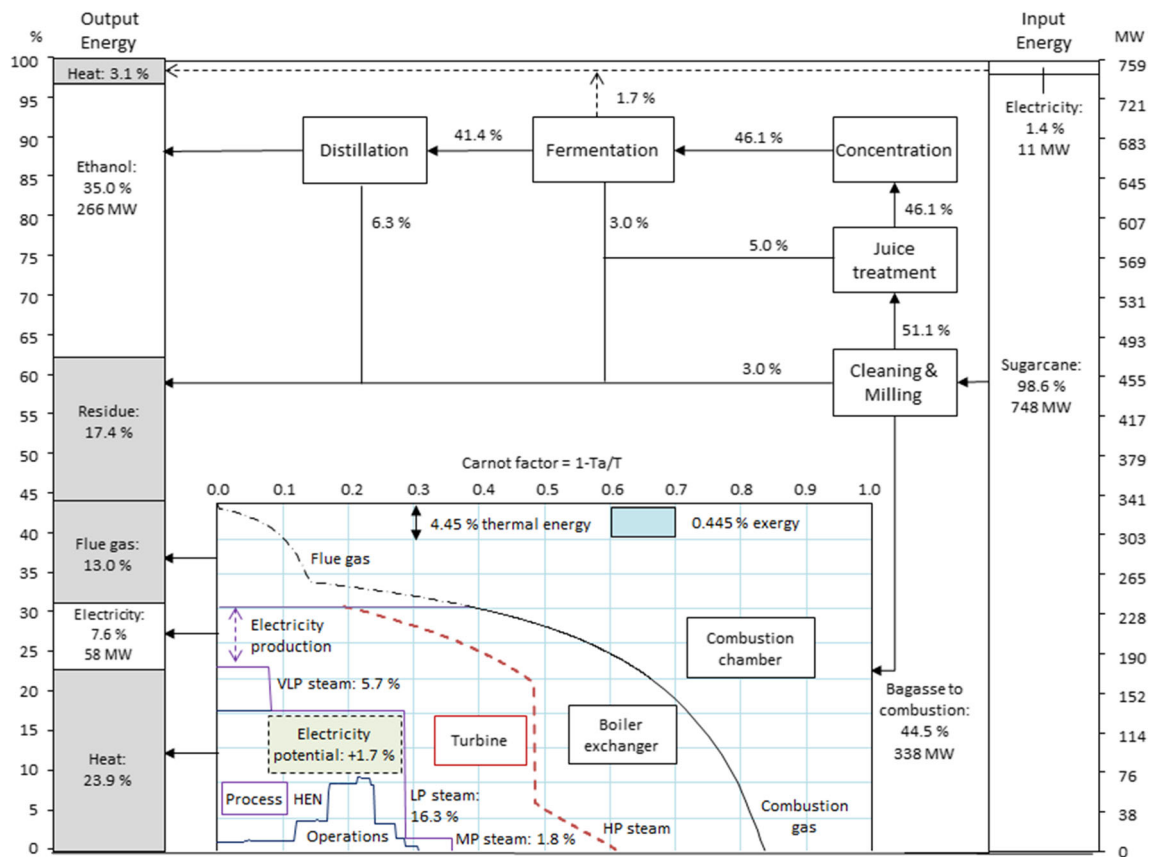


Fig. 7 Ethanol production—plant-wide energy diagram

44.5%, is separated from the juice and sent to the boiler. The physical and chemical treatment of juice produces 5.0% as rejects, mainly as filter cake, which is usually reused in fields as fertilizers. The exothermic reactions of fermentation produce 1.7% heat. During fermentation, yeasts use a part of sucrose in the juice for their growth. The resulting excess yeast is then purged. In the ethanol purification step, which is composed of four distillation columns, by-products of fermentation reactions are removed, corresponding to 6.3% inlet energy. The main source of rejects is the stillage of the beer and rectification columns. The stillage is mainly composed of water, glycerol, acetic acid, propionic acid, lactic acid, and fusel oil. The beer column stillage can be used in fields or can be burned in a boiler after its concentration is increased to 65% solids. The produced ethanol amounts to 35.0% of the inlet energy, while the total residue from process operation residue accounts for 17.4%. The boiler-turbine-process ETD at the bottom of Fig. 7 shows the conversion of bagasse combustion enthalpy. The bagasse combustion is used to produce electricity and MP and LP steams for the process. The heat from MP steam and LP steams is cascaded through the HEN and process operations until ambient temperature. In this diagram, the LP steam consumption for the process is maximal. By HEN modifications, it is possible to reduce the LP steam consumption until the minimum, which corresponds to the top of the

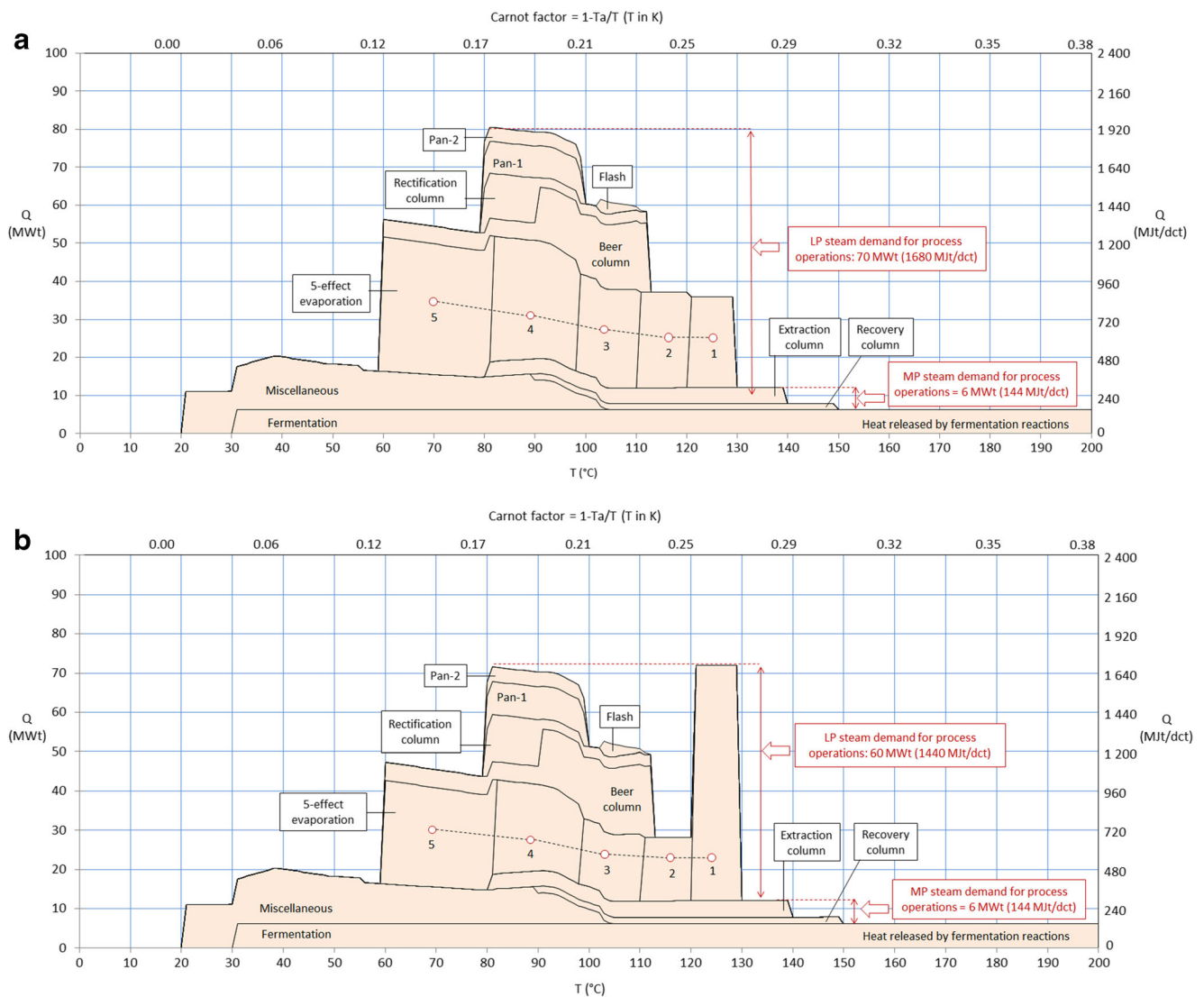
process operations curve. This reduction can result in an increase in electricity output by the production of VLP steam through a condensing turbine. The diagram shows the potential for an increase in electricity production, which amounts to the area of 1.7% exergy. The actual increase in electricity production can be evaluated by multiplying this value by the isentropic efficiency.

Analysis of Plant-Wide Heat Cascade in the Ethanol and Sugar Production

The results for the ethanol and sugar production are hereafter presented in the same structure as for the autonomous ethanol production, i.e., evaluation of heat cascade through (1) the process operations, (2) the HEN, and (3) the entire plant.

Analysis of the Process Operations, Ethanol-Sugar Plant

As shown in Fig. 8a, the minimum MP and LP steam consumptions amount to 6 and 70 MWt, respectively. The operations requiring MP steam are the extraction column and the glycol recovery column. The main operations requiring LP steam are the 5-effect evaporation system, the distillation



Figs. 8 Ethanol and sugar plant: ETD of the process operations. **a** ETD of the process operations with a classical 5-effect evaporation system. **b** ETD of the process operations with an integrated 5-effect evaporation system

through the beer column and the rectification column, and the boiling pans in the sugar process. The ETR termed “miscellaneous” gathers operations with a low flow rate of cascaded heat, e.g., non-isothermal mixings, cooling of mass outlets to ambient temperature, and heat losses from equipment. The fermentation reactions are slightly exothermic, releasing 125 MJ/dct. This heat has to be removed from the reactors to maintain the yeast activity, which is optimal around 30–35 °C. The ETR corresponding to the fermentation considers the enthalpy of reaction, as the composition changes from the inlet to the outlet.

In the sugar process, the treated juice is concentrated from 14 to 65% through a 5-effect evaporation system. This operation requires evaporating 1400 kg water/dct, which corresponds to around 3080 MJ/dct (1400 kg/dct * 2.2 MJ/kg). In a classical 5-effect evaporation system, where all condensation heat from an effect is used in the next effect until the last

one, 616 MJ/dct heat is provided to the first effect at 130 °C, and heat is gradually cascaded to the other effects until the vapor outlet of the fifth effect at 60 °C. The corresponding heat cascade through the 5 effects is visible on the ETD. Figure 8a shows that this operation of juice concentration crosses the maximum of the flow rate of cascaded heat, which is located at 82 °C and corresponds to (70 + 6) MWt of LP and MP steams. Therefore, the 5-effect evaporation system can be reorganized to reduce total heat consumption in the process. If the heat load to the first effect is increased to 1440 MJ/dct (60 MWt), 410 MJ/dct is necessary through the four next effects to achieve the value required for evaporation (total = 3080 MJ/dct). Consequently, the remaining heat from the first effect, 1030 MJ/dct can satisfy the beer and rectification columns, the flashing system, and the boiling pans. Figure 8b presents this situation, where the global LP steam consumption is reduced from 1680 to 1440 MJ/dct.

Analysis of the HEN, Ethanol-Sugar Plant

Table 3 presents the heat demands and sources for the ethanol-sugar process with a classical 5-effect evaporation system, i.e., nonoptimally integrated with the remaining part of the process. The minimum individual temperature difference ($\min \Delta T$) is presented for each stream in the rightmost column. PS14 refers to the cooling of vapor condensate coming from juice concentration after a 5-effect evaporation system. The reboiler of the extraction column (PD5) and the reboiler of the glycol recovery column (PD6) require MP steam at 180 °C, while the other demands can be satisfied with LP steam at 135 °C. The maximum energy consumption of the process,

i.e., without heat recovery through the HEN and without operation modification, is equal to the total demand, i.e., 6 MWt of MP steam and 119 MWt of LP steam.

Figure 9 represents the heat cascade through the process operations and the HEN with maximum energy consumption. It is assumed that all the heat from PSs is released to the ambient, at 20 °C. As can be seen, the total flow rate of cascaded heat as a function of temperature is constant from the MP and LP steam levels to ambient temperature. This results from the principles of energy conservation and entropy increase. The difference between the total energy consumption 125 MWt in the process, which includes the operations and the HEN, and the maximum height of the process operations

Table 3 Ethanol and sugar plant—data extracted for HEN design

ID	Description	\dot{Q} (MWt)	\dot{Q} (MJt/ tdc)	T_c (°C)	T_h (°C)	$\min \Delta T$ (°C)
Process heat demands						
PD1	Ethanol line: fermentation product before beer column	13.5	324	31	90	5
PD2	Ethanol line: juice before flash tank	17.0	184	35	110	5
PD3	Ethanol line: reboiler of rectification column	3.0	72	108	109	5
PD4	Ethanol line: reboiler of beer column	18.3	439	113	114	5
PD5	Ethanol line: reboiler of extraction column	4.3	102	138	140	5
PD6	Ethanol line: reboiler of glycol recovery column	2.1	51	150	151	5
PD11	Sugar line: first boiling pan	8.1	194	93	94	5
PD12	Sugar line: second boiling pan	3.6	86	93	94	5
PD13	Sugar line: drying sugar crystals	2.0	48	30	85	5
PD14	Sugar line: juice before flash tank	22.4	537	30	110	5
PD15	Sugar line: 5-effect evaporator—evaporation	8.5	204	93	128	5
	Sugar line: 5-effect evaporator—juice preheating	22.8	547	128	130	5
Total		125.9	3021			
Process heat sources						
PS1	Ethanol line: fermenters	5.8	139	30	31	5
PS2	Ethanol line: condenser of beer column	3.8	92	58	60	8
PS3	Ethanol line: condenser of rectification column	12.8	307	78	80	8
PS4	Ethanol line: condenser of extraction column	3.7	88	78	80	8
PS5	Ethanol line: juice before fermentation	13.0	313	30	92	5
PS6	Ethanol line: vapor from flash tank	1.7	41	100	102	8
PS7	Ethanol line: rectification column stillage	2.1	51	30	110	5
PS8	Ethanol line: beer column stillage	15.5	371	30	110	5
PS11	Sugar line: vapor from the fifth effect of evaporator	34.1	817	40	62	8
PS12	Sugar line: vapor second boiling pan	3.8	92	78	80	8
PS13	Sugar line: vapor first boiling pan	8.5	204	78	80	8
PS14	Sugar line: condensates from 5-effect evaporator	9.2	220	50	95	5
PS15	Sugar line: vapor from flash tank	2.6	61	100	102	8
Total		116.5	2797			

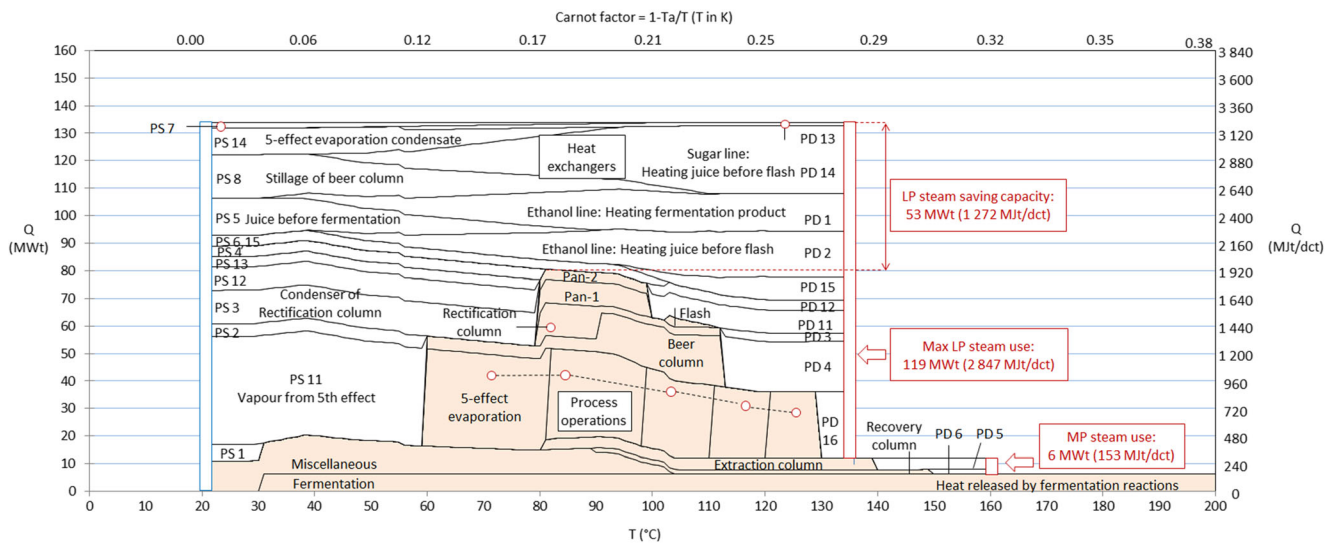


Fig. 9 Ethanol and sugar plant: ETD of process operations and HEN with maximum energy consumption

part is equal to the capacity of thermal energy savings through HEN modifications. This thermal energy savings capacity, 53 MWt, corresponds to 14 MWe exergy savings. This value results from multiplying the capacity of thermal energy savings (53 MWt) with the Carnot factor (0.28) shown above the diagram. These exergy savings can lead to an increase in electricity production through a turbine. Table 4 presents the results of energy savings through HEN modifications with several temperature difference factors $f_{\Delta T}$, from 0 to 3. The electricity production increase corresponding to the thermal energy savings in the HEN is shown at the bottom of the table; the isentropic efficiency of the steam turbine is assumed to be equal to 0.85. The maximum electricity production increase presented in Table 4, 12 MWe, is smaller than the value resulting from the capacity of thermal energy saving multiplied by the Carnot factor of the LP steam (0.28), 14 MWe, since the latter assumes isentropic steam expansion.

The global guidelines to save energy through the HEN are the following (Fig. 9). Firstly, the following process heat demands can be satisfied with available process heat sources: the fermentation product at the beer column inlet (PD1), the juice

before the flash tank in the ethanol line (PD2), and the juice before the flash tank in the sugar line (PD14). Their corresponding large ETRs clearly show that these demands can be heated by the following process sources: the condensate from the 5-effect evaporation system (PS14), the stillage from the beer column (PS8), the juice before fermentation (PS5), and the vapor from the flash tank (PS6 and PS15). Other valuable sources are the condenser of the rectification column (PS3), the condenser of the extraction column (PS4), and the vapor from the sugar pans (PS12 and PS13). To further decrease the energy consumption, it is necessary to modify process operations. For instance, heat from the first effect of the 5-effect evaporation system can be used in the reboilers of the beer and rectification columns; heat from the second effect can be used for the sugar boiling pans or sent to the reboilers of the beer and rectification columns if the pressure inside them is reduced (which would move the ETRs of the beer and rectification columns to the left in Fig. 9); the extraction and recovery columns can be replaced by molecular sieves. All these HEN or PO modifications would move down the top curve of the ETD shown in Fig. 9.

Table 4 Ethanol and sugar plant—results of thermal energy savings

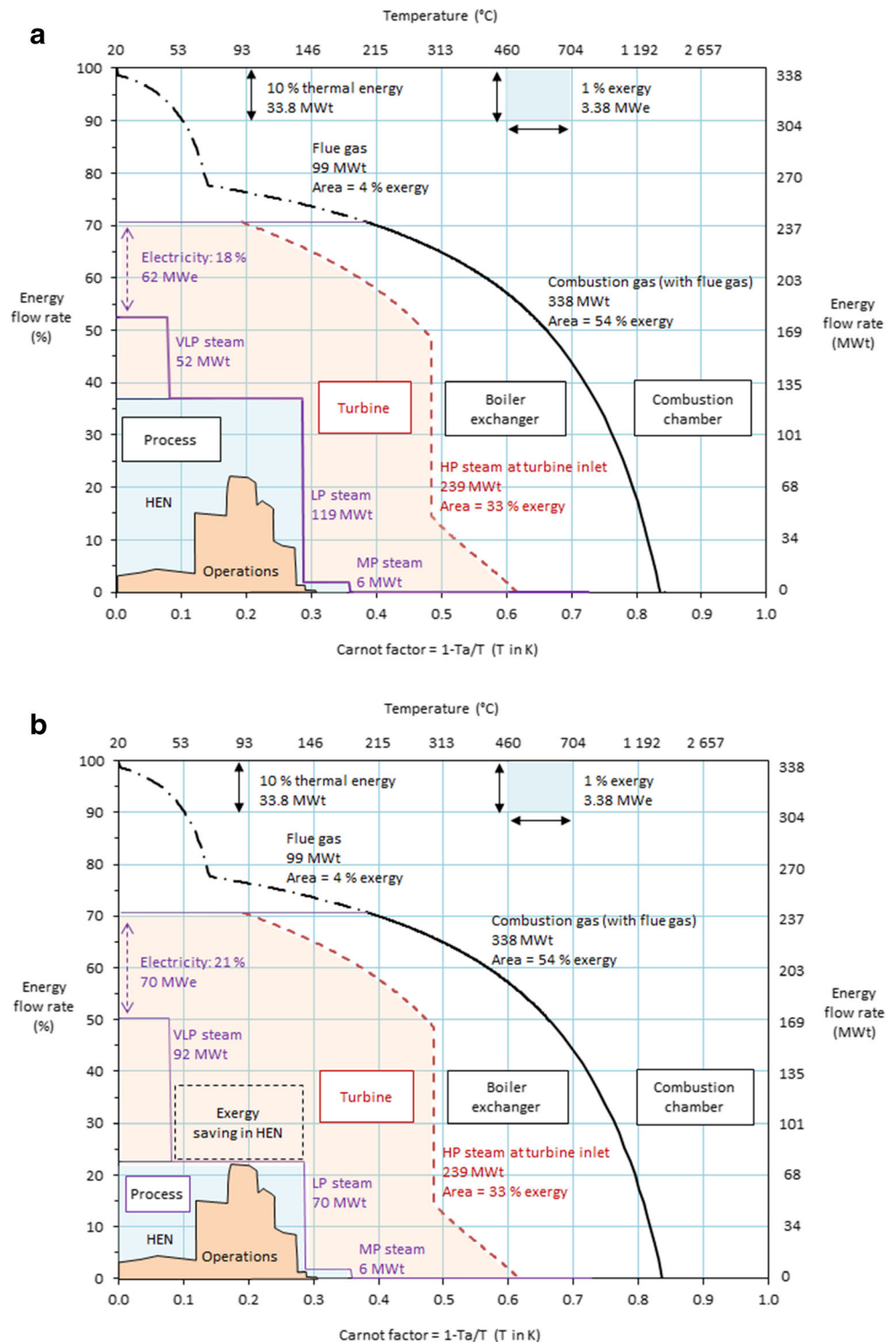
$f_{\Delta T}$ for heat recovery		0	1	2	3	Without heat recovery
Pinch temp.	°C	80	72	64	78	—
LP steam	MWt	65.8	75.7	85.5	95.0	119.5
Consumption	MJt/dct	1580	1816	2052	2281	2868
MP steam	MWt	6.4	6.4	6.4	6.4	6.4
Consumption	MJt/dct	153	153	153	153	153
Electricity prod. increase	MWe	12.4	10.2	7.9	5.7	0.0
	MJe/dct	299	244	189	136	0

Analysis of the Entire Ethanol-Sugar Plant: Boiler, Turbine, Process Operations, and HEN

The boiler-turbine-process ETD of Fig. 10a presents the progressive transfer of heat from right to left through the components of the plant as a function of the Carnot factor. It includes

the bagasse combustion, the heat transfer through the boiler exchanger for producing high-pressure (HP) steam, the expansion of HP steam through a turbine with the production of electricity, and the heat cascade through the process (HEN and PO) with a classical 5-effect evaporation system. The heat cascade through individual process operations and heat

Figs. 10 Ethanol and sugar plant: boiler-turbine-process ETD. **a** Boiler-turbine-process ETD: case with maximum energy consumption in the HEN. **b** Boiler-turbine-process ETD: case with minimum energy consumption in the HEN



exchangers were shown in detail in Figs. 8a and 9. The ETD of the process operations and heat exchangers together in Fig. 9 is the detail of the process region of Fig. 10a. Starting from the bagasse combustion at the right of the diagram, the curve of the resulting combustion gas represents its cumulative thermal energy content. The combustion gas is sent to the boiler exchanger to produce HP steam. The resulting flue gas (dot-dashed line) leaves the plant at 200 °C; the change in the slope of the flue gas curve below 100 °C results from the vapor condensation at atmospheric pressure. The proportion of energy lost through the flue gas depends on its temperature and the bagasse composition, including its moisture. The HP steam curve is shown by the dashed red line and results from heating water from 90 to 510 °C at 90 bars, which implies vaporization at 303 °C, represented by the vertical section of the curve at this temperature. The exergy content of the HP steam is 33% (area at the left of the curve) of the combustion energy of the bagasse. This HP steam is sent to a turbine system to produce electricity and medium-pressure (MP) and low-pressure (LP) steams required for the process. In Fig. 10a, the MP and LP steam demands for the process correspond to the maximum energy consumption to the HEN. Excess steam is expanded to very low pressure (VLP) through a condensing turbine. It is assumed that the isentropic efficiency is equal to 85%. As the steam expansion is not isentropic, the exergy at the turbine outlet (electricity, MP, LP, and VLP steams) is less than at the inlet (HP steam). The difference between the maximum height of the HP steam curve at the turbine inlet (71%) and the maximum height of the MP, LP, and VLP steam curve at the turbine outlet (53%) is equal to the amount of electricity produced (18%) by expansion through the turbine system.

For the production of ethanol and sugar, the bagasse with a moisture content of 50% coming from the milling is burned in the boiler. The combustion reactions occur at a very high temperature and release 338 MWt thermal energy, which corresponds to about 338 MWe as the quality factor of the fuel (ratio between energy and exergy) is close to one. In the boiler-turbine-process ETD, each internal square represents 1% exergy (3.38 MWe) of the combustion total. The combustion gas results from the heating of the air inlet with the energy released by bagasse oxidation and the change in its composition. The hot combustion gas contains 100% of the thermal energy (338 MWt) and 54% of the exergy (area at the left of the curve). This gas is sent to the boiler exchanger to produce HP steam. The combustion gas leaves the boiler exchanger at 200 °C; the resulting flue gas contains 29% of the thermal energy (99 MWt) and about 4% of the exergy (area at the left of the flue gas curve). The produced HP steam contains 71% thermal energy of the combustion total and 33% exergy, which corresponds to the number of internal squares at the left of the HP steam curve. The HP steam feeds the turbine system to produce electricity and MP and LP steams for the

process. Heat from MP and LP steams is cascaded to ambient temperature through the operations and the heat exchanger network (HEN). The border between the operations and the heat exchangers is shown inside the process area. In Fig. 10a, we assumed that the maximal thermal energy consumption is required for the process, i.e., without heat recovery through the HEN. The process, with a classical 5-effect evaporation system and maximum energy consumption in the HEN, requires 6 MWt of MP steam and 119 MWt of LP steam. Excess steam is expanded to VLP steam. The turbine produces 62 MWe of electricity (18% of the total combustion exergy).

Figure 10b presents the situation with minimum energy consumption to the process, i.e., 6 and 70 MWt of MP and LP steams, respectively. The exergy saving in the process is shown by the area bordered by a black dashed line, which is equal to approximately 3%. This exergy saving makes it possible to increase the electricity production from 62 to 70 MWe. This increase in electricity production is less than the value in Table 4 (12 MW) as the VLP steam at the condensing turbine outlet still has some exergy in Figs. 10 ($T = 45$ °C, Carnot factor = 0.08).

Figure 11 presents the plant-wide energy balance for ethanol and sugar production. Energy inlets and outlets are shown at the right and the left of the diagram, respectively. Values are expressed in percentage of total energy and MW. The input energy, which amounts to 756 MW, is composed of combustion enthalpy of sugarcane (99.0%) and electricity (1.0%) used in some equipment. Electrical energy is transformed into mechanical energy and leaves the plant as heat. At the sugarcane cleaning and milling step, bagasse, whose combustion energy amounts to 44.5%, is separated from the juice and sent to the boiler. The rejects from cleaning and milling correspond to 3.0% of the total inlet energy by their combustion enthalpy. The physical and chemical treatments of juice in the ethanol and sugar lines produce 2.2 and 3.3% of rejects, respectively, mainly as filter cake, which is usually reused in fields as fertilizer. The exothermic reactions of fermentation produce 1.0% heat. During fermentation, the yeasts use a part of sucrose in the juice for their growth. The resulting excess yeast is then purged. In the ethanol purification step, which is composed of four distillation columns, by-products of fermentation reactions are removed, corresponding to 3.6% of the inlet energy. The main sources of rejects are the stillage of the beer column and the rectification column. These are mainly composed of water, glycerol, acetic acid, propionic acid, lactic acid, and fusel oil. The stillage of the beer column can be used in fields or sent to the boiler after its concentration is increased to 65% solids. The produced ethanol and sugar amount to 16.2 and 21.9% of the inlet energy; the total residues from process operations account for 15.4%. The boiler-turbine-process ETD at the bottom of Fig. 11 shows the conversion of bagasse combustion enthalpy, which accounts for 44.5% of the inlet energy. The bagasse combustion is used to produce electricity

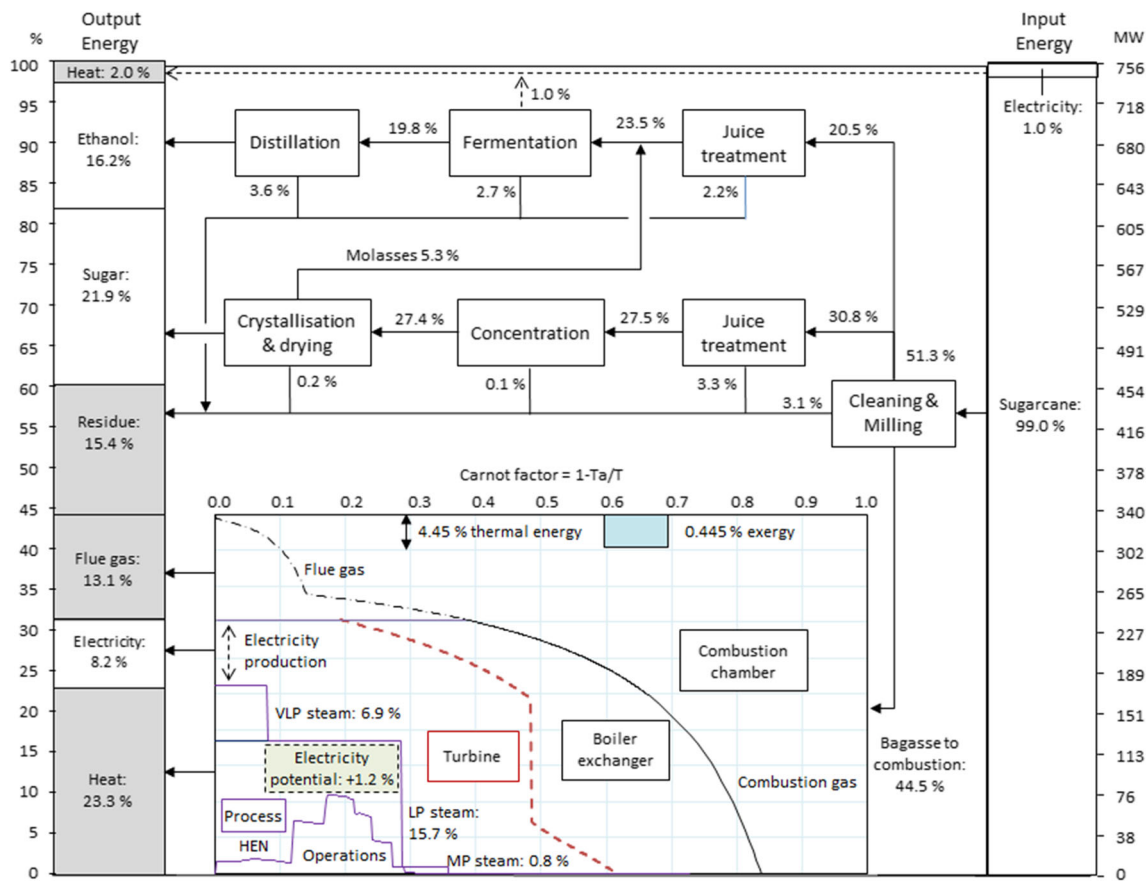


Fig. 11 Ethanol and sugar plant—plant-wide energy diagram

and MP and LP steams for the process. The heat from MP steam and LP steam is cascaded through the HEN and process operations until ambient temperature. In this diagram, the LP steam consumption to the process is maximal. The resulting electricity production amounts to 8.2%. By HEN modifications, it is possible to reduce the LP steam consumption until the minimum, which corresponds to the top of the process operations curve. This reduction can result in an increase in electricity output by the production of more VLP steam through a condensing turbine. The diagram shows the potential of an increase in electricity production, 1.2% exergy, which corresponds to the area limited by a dashed line inside the process part. The actual increase in electricity production can be evaluated by multiplying this value by the isentropic efficiency, e.g., 0.85. Consequently, the electricity production amounts to 9.2% in the case of minimum steam consumption to the process.

Discussion

The profitability of the ethanol and ethanol-sugar processes can be increased by improving the HEN, using pinch analysis, or other methods (Nguyen et al. 2010; Sreepathi

and Rangaiah 2014; Ayotte-Sauvé et al. 2017). Reducing the thermal energy consumption to the HEN makes it possible either to produce more electricity through a condensing turbine or to use the excess bagasse for producing value-added chemicals (Ensinas et al. 2007; Lopes Silva et al. 2014; Santos et al. 2016). Figure 12 shows a first proposed HEN for the ethanol plant, using the values given in Table 1, which involves a 5-effect system to concentrate the juice before fermentation. In this figure, the HEN representation is consistent with the ETD and the common convention regarding functions of a single variable; that is, enthalpy is the cumulative heat content as a function of temperature, and heat is transferred from right to left. This HEN leads to a reduction of 50.1 MWt of LP steam; this saving corresponds to a possible production increase by about 14 MWe of electricity, considering the Carnot factor of LP steam. On the grid diagram of Fig. 12, the heat demand corresponding to the first effect of the concentrating system, PD6, was segmented into two parts, corresponding to two different heat capacity rates: from 93 to 128 °C for the juice preheating and from 128 to 129 °C for the evaporation (PD6 is heated by heater H5). This HEN has the following advantages. Firstly, this network is simple and avoids stream splitting, which may lead

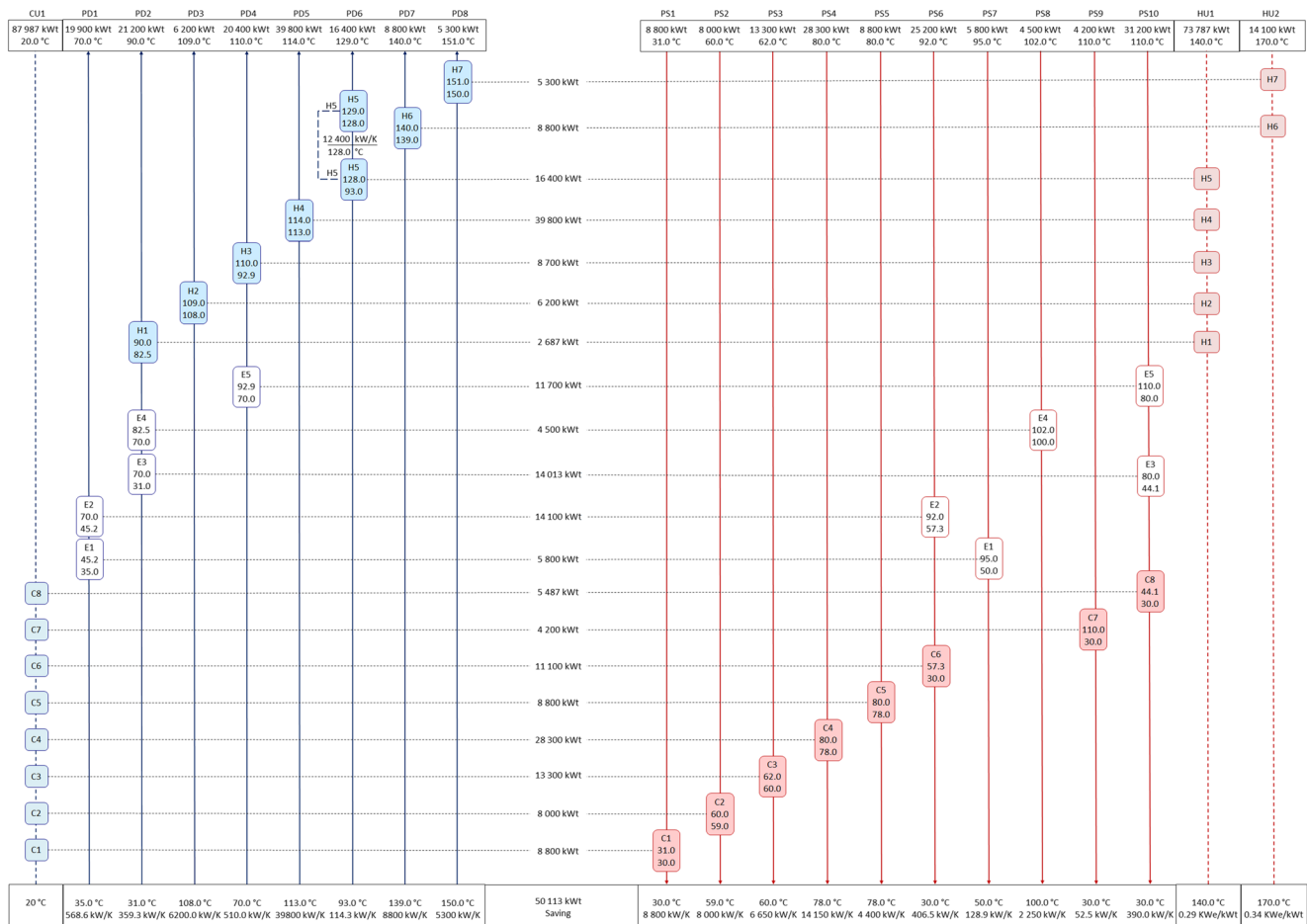


Fig. 12 Ethanol plant—HEN to reduce the thermal energy consumption (solution 1)

to operability difficulties. Secondly, the heat from the condensers of the distillation columns and juice concentrator's fifth effect (PS2 to PS5) is released only through coolers C2 to C5 and is not used in process-process exchangers; this facilitates the operability and reduces the investment and operating costs, including piping and pumping. Finally, this solution requires only 5 process-process exchangers, and the total number of exchanger units is equal to the minimum value (20), considering the cooling utility, the 8 process heat demands, the 10 process heat sources, and the two heating utilities. In the proposed network, heat from PS9, which corresponds to the cooling of the rectification column stillage from 110 to 30 °C, is not recovered (this heat is rejected by cooler C7) since its heat capacity (kW/°C) and total heat content are small. However, the rectification column stillage may be mixed with the beer column stillage PS10 if the operation allows it; this mixing would lead to a further reduction of the heat consumption to the HEN. E1 refers to a process-process exchange from the condensate coming from the juice through the 5-effect evaporator system, PS7, to the juice before liming, PD1. This indirect-contact heat exchanger can be removed and replaced by a direct contact heat transfer by simply using

the condensate PS7 to wash the sugarcane at the milling step, if the composition of the condensate allows it.

Figure 13 presents the corresponding flow rate of cascaded heat through the exchangers between the balanced hot and cold composite curves. It is possible to reduce further the thermal energy consumption in the HEN without recovering heat from coolers C2 to C5 (less accessible distillation condensers) by decreasing the flow rate of cascaded heat from the heating utility HU1 to the ambient in the green region of Fig. 13. This region includes the coolers C6, C7, and C8, the process-process heat exchangers, and the heaters H1 and H3. To reduce the flow rate of cascaded heat through the HEN in the entire temperature interval between the heating utility and the cooling utility, a set of modifications, termed “bridge,” which starts from a cooler and finishes at a heater is necessary (Bonhivers et al. 2015). Bridge modifications lead to a second solution, presented in Fig. 14. This HEN leads to 7% more energy savings, still implies the minimum number of exchanger units (20), and does not involve heat recovery from the condensers of the distillation columns and juice concentrator's fifth effect (PS2 to PS5); this heat is released through coolers C2 to C5. However, it includes one supplementary process-process heat exchanger and the splitting of the stream

Fig. 13 Ethanol plant—flow rate of cascaded heat through the HEN of solution 1 between the balanced hot and cold composite curves

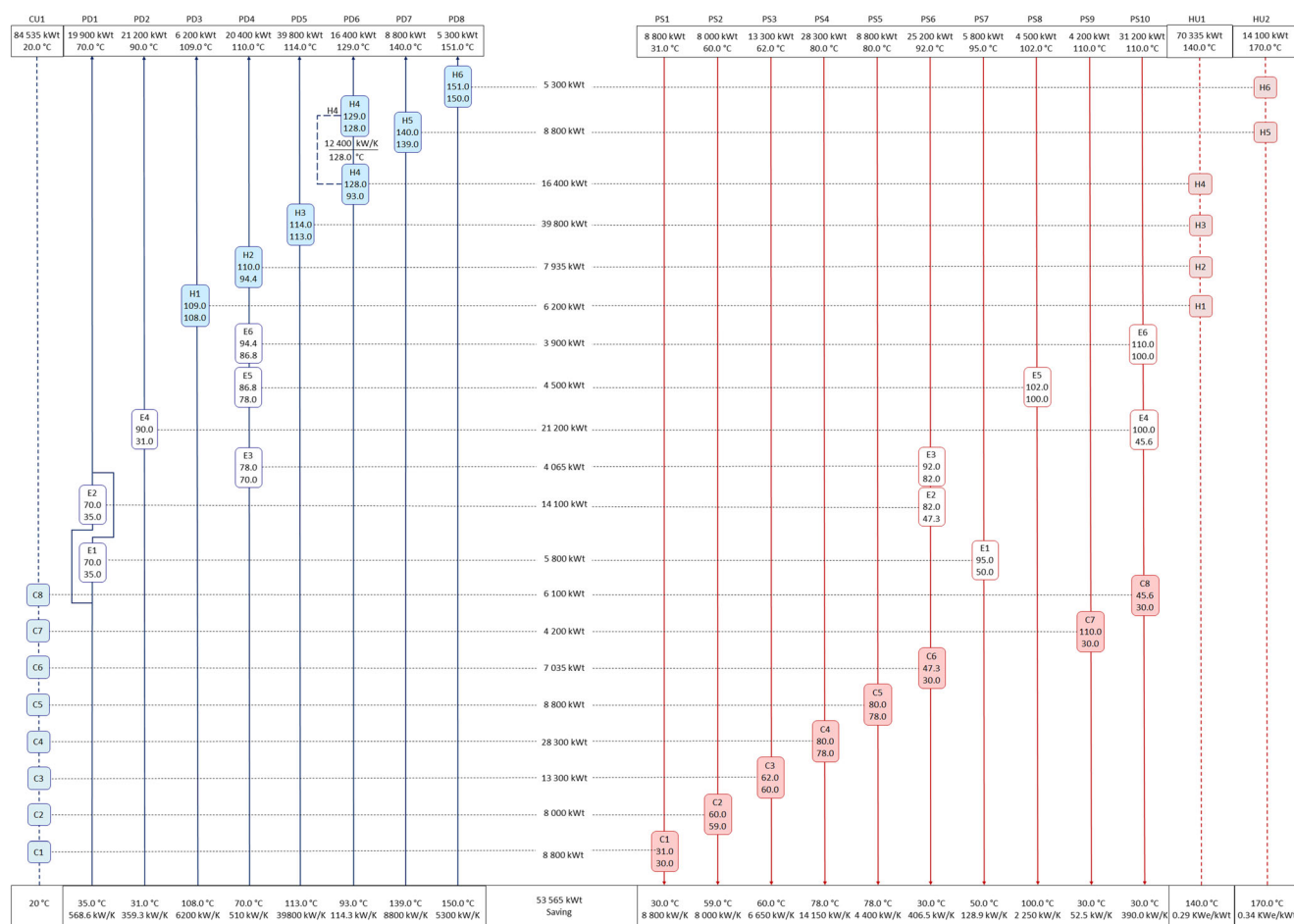
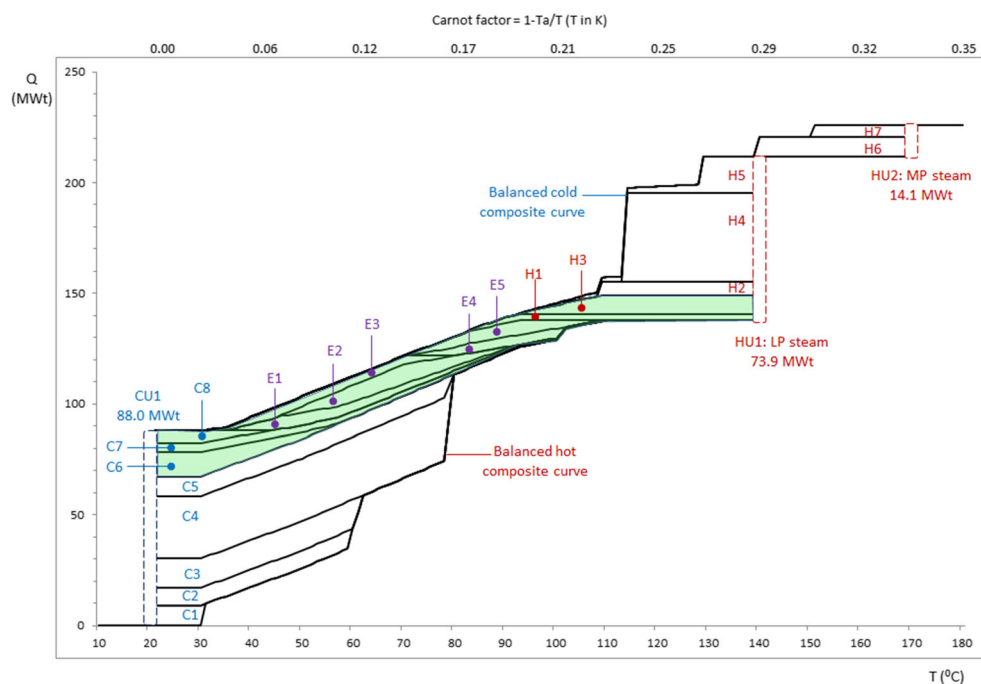


Fig. 14 Ethanol plant—HEN to reduce the thermal energy consumption (solution 2)

corresponding to the juice before liming (PD1), which adds complexity to the network (Kemp Ian 2006).

Table 5 presents the economic results corresponding to both solutions. The costs of equipment with other sizes than presented in the literature were calculated according to Eq. 9 with the exponent equal to 0.7, which is commonly used for heat exchangers (Humbird et al. 2011).

$$\text{New cost} = \text{Original Cost} \left(\frac{\text{New Size}}{\text{Original Size}} \right)^{0.7} \quad (9)$$

The Chemical Engineering Plant Cost Index (CEPCI) was employed to calculate the prices in 2020, which is the reference year of this study. The data applied to determine the investment cost adopted was annualized using 200 days as the operating season. The Total Fixed Capital Cost (TFCC) was evaluated by multiplying the purchase equipment cost by 4.8. We considered that the steam saving in the HEN led to an increase in electricity production through a condensing turbine. It was assumed an isentropic efficiency for the LP steam expansion equal to 80% and a price of electricity equal to 0.07 USD/kWh. The simple payback period (SPP) for both solutions is less than or equal to 1 year. The data do not include the money savings resulting from the reduction in the number and size of heaters and coolers in the two solutions, in comparison with the HEN without heat recovery.

Given that two viable and interesting solutions have been found, from both the energy and cost points of view, the best choice would depend on currently installed equipment and the local input of plant engineers. For example, if a condensing turbine is already installed and allows the steam expansion corresponding to solution 2, this solution leads to reduced flowrate of cascaded heat (at lower temperature) and increased

electricity production. The boiler-turbine-process ETD (Fig. 6a) describes the relation between heat cascade and electricity production.

The present production of sugar and ethanol, which are commodities, results in a large excess of thermal energy and low profitability. The profitability of sugar and ethanol plants could be increased by integrating them with various chemical or food processes and organizing value chain industry clusters (Hackl et al. 2011; Hiete et al. 2012). The integration could provide opportunities to share material or energy flows (sugar, ethanol, CO₂, water, high-pressure steam for the extraction of value-added chemicals, high-quality molasses, heat, electricity, etc.), the cold and vacuum system, the juice concentration system, the water treatment system, equipment, logistics, labor costs, marketing, etc. For example, high-quality molasses can be obtained using existing equipment in the sugar process; these can be the starting material for the production of value-added chemicals. Other chemical processes can also benefit from integration opportunities related to the cluster. The food industry evolves in an environment of worldwide competition. Sharing resources can lead to competitive advantages, as the price of food is strongly dependent on the quality, the sterilization, and the validity period. The integration of several processes into a value chain industry cluster can lead to a reduction of production costs and an increase in the profitability in the sugarcane industry (Bonhivers et al. 2019, Hackl and Harvey 2012, 2013, Matsuda et al. 2009, Perry 2013).

In the energy transfer diagrams, the actual flow rate of cascaded heat through the sugarcane-based production of ethanol was presented; this includes the boiler for the fuel combustion, the boiler exchanger for the production of HP steam, the turbine for steam expansion and electricity production, and the process operations and heat exchangers. The flow rate of

Table 5 Autonomous ethanol plant—economic results from heat savings to HEN

Exchanger Id	Area (m ²)	TFCC (USD)	Heat savings (kWt)	Increase in electricity sales (USD/y)	SPP (y)
<i>Solution 1</i>					
E1	200	293,566	5800	400,200	0.7
E2	851	786,190	14,100	972,900	0.8
E3	1221	1,004,352	14,013	966,897	1.0
E4	185	278,026	4500	310,500	0.9
E5	884	806,545	11,700	807,300	1.0
Total		3,168,678	50,113	3,457,797	0.9
<i>Solution 2</i>					
E1	296	383,504	5800	400,200	1.0
E2	1161	970,479	14,100	972,900	1.0
E3	313	398,362	4065	280,485	1.4
E4	1744	1,280,213	21,200	1,462,800	0.9
E5	245	336,719	4500	310,500	1.1
E6	271	361,357	3900	269,100	1.3
Total		3,730,634	53,565	3,695,985	1.0

cascaded heat through a system is indicated by the ETR, which is equal to the difference between the outlet and inlet enthalpy curves as a function of temperature. An explanation as to why the flow rate of cascaded heat through a system has not been formalized in the literature may come from a difference between two commonly used conventions. (1) In human history, temperature was related to the sky, weather, and the common thermometer, using the principle of thermal expansion of a liquid. Consequently, temperature was often represented on the vertical axis (ordinate). In accordance with this perspective, the following terms are used to describe temperature: low or high, decrease or increase, degradation, degree, energy quality level, heat cascade, etc. Therefore, the composite curves in pinch analysis are represented with temperature on the vertical axis. In accordance with the conventions of pinch analysis, HENs are usually represented on a grid diagram with vertical heat transfers from top to bottom. (2) The second common convention is in regard to functions of a single variable, where the independent variable is represented on the horizontal axis (abscissa). The enthalpy change and flow rate of cascaded heat are functions of temperature. This difference between the two usual conventions may have created confusion. Temperature is not a function of the flow rate of cascaded heat since a function must be single-valued, while the flow rate of cascaded heat is a function of temperature. For this reason, the temperature and enthalpy variables are represented on the horizontal and vertical axes in the ETD, respectively. Accordingly, HENs in this paper are also represented with horizontal heat transfers from right to left (Figs. 12 and 14). This representation is consistent with the ETD and the common convention regarding functions of a single variable, which is here temperature or Carnot factor.

It is worth noting that grand composite curves with several temperature difference factors $f_{\Delta T}$ can also be shown together on the ETD. The grand composite curve represents the heat load of the potentially coldest heating and hottest cooling utilities with infinite heat transfer coefficients, after taking into account the constraints of minimum temperature difference on process heat sources and demands. In reality, the grand composite curve with $f_{\Delta T}=0$ is the curve at the top of the process operations part on the ETD. If grand composite curves with $f_{\Delta T}>0$ are represented on the ETD, these will be located above the grand composite curve with $f_{\Delta T}=0$. The portion between grand composite curves with $f_{\Delta T}>0$ and the grand composite curve with $f_{\Delta T}=0$ represents the flow rate of cascaded heat through the minimum temperature difference required for each process heat source and demand. In other words, this layer represents the flow rate of cascaded heat resulting from shifting the hot and cold composite curves to consider the constraints of minimum temperature difference on process heat demands and sources. Consequently, the region below the grand composite curve with $f_{\Delta T}>0$ on the ETD represents the sum of the flow rates of heat cascaded

through the process operations and through the minimum temperature differences required to process demands and sources. The region below the grand composite curve on the ETD corresponds to the empty right part of the grand composite curve on the classical representation used in pinch analysis, i.e., with temperature and heat load on the vertical and horizontal axes, respectively. The region above the grand composite curve on the ETD shows the flow rate of cascaded heat through the HEN and corresponds to the empty left part of the grand composite curve on the classical representation after shifting to the right of the latter curve until reaching the actual consumption of heating utilities in the HEN. In other words, the regions below and above the grand composite curve on the ETD correspond to the empty right and left parts of the balanced grand composite curves. In the boiler-turbine-process ETD, we considered the grand composite curve with $f_{\Delta T}=0$ to estimate the heat savings potential by HEN modifications. Using a grand composite curve with $f_{\Delta T}>0$ makes it possible to estimate the energy savings potential considering the constraints of minimum temperature difference between process heat demands and sources.

Conclusion

For the first time, the entire heat cascade through the components of ethanol and sugar production has been analyzed. A site-wide analysis was presented using both new diagrams and refinements to energy transfer diagrams (ETD). Data was organized differently from the usual conventions in order to strengthen the connections between the diagrams and the heat integration concepts. The flow rate of cascaded heat through a system (e.g., an individual component) is shown by the energy transfer region (ETR). The ETR of a system is equal to the difference between the outlet and inlet enthalpy curves. Therefore, the difference between the HCC and the CCC is equal to the flow rate of cascaded heat through the process operations, while the difference between the balanced CCC and the balanced HCC is equal to the flow rate of cascaded heat through the HEN. Enthalpy and the independent variable T are represented in the proposed diagrams on the vertical and horizontal axes, respectively, and heat is transferred from right to left.

Proposed new or refined graphical tools include the following: the boiler-turbine-process ETD (Figs. 6 and 10), the plant-wide energy diagram (Figs. 7 and 11), the link between the hot and cold composite curves (Figs. 4 and 13), and the corresponding HEN representation on grid diagrams (Figs. 12 and 14). The inclusion of the Carnot factor as one of the horizontal axes on most of the presented figures underlines the connection between heat cascade and exergy reduction. For example, the area of the ETR plotted as a function of Carnot factor is equal to the reduction of the exergy through

a system. Heat above ambient temperature can be transferred until the ambient. Consequently, the area at the left of the cumulative heat content curve of a stream (e.g., combustion gas) as a function of the Carnot factor on the ETD is equal to its total exergy. The exergy of the steam at the turbine inlet is always greater than or equal to the produced mechanical work plus the exergy of the steam at the outlet. This results from the second principle of thermodynamics, which states that the total entropy of an isolated system does not decrease. The boiler-turbine-process ETD uses this information to organize data helpful to energy integration.

In autonomous plants, the produced ethanol and electricity correspond to about 35.0% and 7.6 to 9.3% of the inlet energy, respectively. In combined ethanol-sugar plants, the produced ethanol, sugar, and electricity correspond to about 16.2, 21.9, and 8.2 to 9.4% of the inlet energy, respectively. The remaining energy (53–57%) leaves the plant as residues or is rejected to the ambient as heat. The plant energy efficiency can be increased by modifying the process operations, the HEN, the turbine system, or the boiler. The analysis of the plant-wide heat cascade through the entire Carnot factor interval, i.e., from close to 1 for the fuel combustion in the boiler until 0 for the heat rejection to the ambient, makes it possible to understand the relation between the combustion energy in a boiler, the exergy of combustion gases and HP steam, the production of electricity through a turbine, and the thermal energy consumption in heat exchangers and process operations. This holistic perspective helps identify opportunities and increase energy performance in the production of ethanol and sugar.

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Compliance with Ethical Standards

Conflict of Interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

Abbreviations C, Cooler, exchanger between a process heat source and a cooling utility; CCC, Cold composite curve; dct, Dry cane ton; E, Heat exchanger between a process heat source and a process heat demand; ETD, Energy transfer diagram; ETR, Energy transfer region; $f_{\Delta T}$, Temperature difference factor; H, Heater, exchanger between a heating utility and a process heat demand; \dot{H} , Enthalpy rate; HCC, Hot composite curve; HEN, Heat exchanger network; HP, High-pressure steam; kW_e, Kilowatt of exergy; kW_t, Kilowatt of thermal energy; LP, Low-pressure steam; Min ΔT , Minimum individual temperature difference (stream-specific contribution); MP, Medium-pressure steam; MJe, Mega joule of exergy; MJ_t, Mega joule of thermal energy; MWe, Megawatt of exergy; MW_t, Megawatt of thermal energy; PD, Process heat demand; PS, Process heat source; PO, Process operations; SPP, Simple payback period; T, Temperature; T_a, Ambient temperature; T_c, Cold-end temperature; TFCC, Total fixed capital costs; T_h, Hot-end temperature; VLP, Very low-pressure steam

References

- Ayotte-Sauvé E, Omid A, Serge B, Navid R (2017) Optimal retrofit of heat exchanger networks: a stepwise approach. *Comput Chem Eng* 106:243–268
- Berntsson T, Harvey S, Morandin M (2013) Application of process integration to the synthesis of heat and power utility systems including combined heat and power (CHP) and industrial pumps, chapter 5 in *Handbook of Process Integration (PI): minimisation of energy and water use, waste and emissions*, Woodhead Publishing Series in Energy No. 61
- Bonhivers J-C, Korbel M, Sorin M, Savulescu L, Stuart PR (2014) Energy transfer diagram for improving integration of industrial systems. *Appl Therm Eng* 63:468–479
- Bonhivers J-C, Svensson E, Berntsson T, Stuart PR (2015) Energy transfer diagram for site-wide analysis and application to a Kraft pulp mill. *Appl Therm Eng* 75:547–560
- Bonhivers J-C, Moussavi A, Alva-Argaez A, Stuart Paul R (2016) Linking pinch analysis and bridge analysis to save energy by heat-exchanger network retrofit. *Appl Thermal Eng* 106:443–472
- Bonhivers J-C, Moussavi A, Hackl R, Adriano MP, Christopher RJ, Mikhail S, Stuart Paul R (2019) Analysis of heat cascade through process components to reduce the energy consumption in industrial systems. *Process Integr Optim Sustain* 3:237–254
- de Souza Dias MO, Modesto M, Ensinas AV, Nebra SA, Filho RM, Rossell CEV (2011) Improving bioethanol production from sugarcane: evaluation of distillation, thermal integration and cogeneration systems. *Energy* 36(6):3691–3703
- de Souza Dias MO, Filho RM, Mantelatto PE, Cavalett O, Vaz Rossell CE, Bonomi A, Lima Verde Leal MR (2015) Sugarcane processing for ethanol and sugar in Brazil. *Environ Dev* 15:35–51
- Dias Marina OS, Ensinas AV, Nebrac SA, Filho Rubens M, Rossell Carlos EV, Wolf MMR (2009) Production of bioethanol and other bio-based materials from sugarcane bagasse: Integration to conventional bioethanol production process. *Chem Eng Res Des* 8(7): 1206–1216
- Efe C, Straathof AJJ, Van der Wielen LAM, (2007). Technical and Economical Feasibility of Production of Ethanol from Sugar Cane and Sugar Cane Bagasse, Delft University of Technology; Department of Biotechnology, <http://resolver.tudelft.nl/uuid:5f3b7381-0da3-4d26-b334-9b4856ecacda>. Accessed 1 Sept 2020
- Ensinas AV (2008) Thermal integration and thermoeconomic optimization applied to industrial process of sugar and ethanol from sugarcane [Integração térmica e otimização termoeconômica aplicadas ao processo industrial de produção de açúcar e etanol a partir da cana-de-açúcar]. PhD Thesis: School of Mechanical Engineering, State University of Campinas; [in Portuguese]
- Ensinas AV, Nebra SA, Lozano MA, Serra LM (2007) Analysis of process steam demand reduction and electricity generation in sugar and ethanol production from sugarcane. *Energy Convers Manag* 48: 2978–2987. <https://doi.org/10.1016/j.enconman.2007.06.038>
- Hackl R, Harvey S (2012) Framework methodology for increased energy efficiency and renewable feedstock integration in industrial clusters. *Appl Energy* 112:1500–1509
- Hackl R, Harvey S (2013) Applying exergy and total site analysis for targeting refrigeration shaft power in industrial clusters. *Energy* 55: 5–14
- Hackl R, Harvey S, Andersson E (2011) Targeting for energy efficiency and improved energy collaboration between different companies using total site analysis (TSA). *Energy* 38:4609–4615
- Hiete M, Ludwig J, Schultmann F (2012) Intercompany energy integration. *J Ind Ecol* 16:689–698. <https://doi.org/10.1111/j.1530-9290.2012.00462.x>
- Humbird D., Davis R., Tao L., Kinchin C., Hsu D., Aden A., Schoen P., Lukas J., Olthof B, Worley M, Sexton D, Dudgeon D, (2011)

- Process design and economics for biochemical conversion of ligno-cellulosic biomass to ethanol, NREL
- Kemp Ian C, (2006) Pinch analysis and process integration - a user guide on process integration for the efficient use of energy
- Linnhoff B, Hindmarsh E (1983) The pinch design method for heat-exchanger networks. *Chem Eng Sci* 38:745–763
- Linnhoff B, Townsend D (1982) Designing total energy system. *Chem Eng Prog* 78:72–80
- Linnhoff B, Dunford H, Smith R (1983) Heat integration of distillation columns into overall processes. *Chem Eng Sci* 38:1175–1188
- Lopes Silva DA, Delai I, Delgado Montes ML, Ometto AR (2014) Life cycle assessment of the sugarcane bagasse electricity generation in Brazil. *Renew Sust Energ Rev* 32:532–547
- Lopez-Castrillon C, Leon JA, Palacios-Bereche MC, Palacios-Bereche R, Nebra SA (2018) Improvements in fermentation and cogeneration system in the ethanol production process: hybrid membrane fermentation and heat integration of the overall process through pinch analysis. *Energy* 156:468–480
- Maréchal F, Kalitventzeff B (1996) Targeting the minimum cost of energy requirement: a new graphical technique for evaluating the integration of utility system. *Comput Chem Eng* 20:225–230
- Maréchal F, Kalitventzeff B (1999) Targeting the optimal integration of steam networks: mathematical tools and methodology. *Comput Chem Eng* 23(Supplement 1):133–136
- Matsuda K, Hirochi Y, Tatsumi H, Shire R (2009) Applying heat integration total site based pinch technology to a large industrial area in Japan to further improve performance of highly efficient process plants. *Energy* 34:1687–1692
- Nguyen DQ, Barbaro A, Vipanurat N, Bagajewicz MJ (2010) All-at-once and step-wise detailed retrofit of heat exchanger networks using an MILP model. *Ind Eng Chem Res* 49:6080–6103
- Perry S, (2013) Total site methodology, chapter 6 of handbook of process integration (PI) – minimisation of energy and water use, waste and emissions, Edited by Klemes J, Woodhead Publishing Series in Energy
- Pina EA, Palacios-Bereche R, Chavez-Rodriguez MF, Ensinas AV, Modesto M, Nebra SA (2017) Reduction of process steam demand and water-usage through heat integration in sugar and ethanol production from sugarcane – evaluation of different plant configurations. *Energy* 138:1263–1280
- Santos VEN, Ely RN, Szklo AS, Magrini A (2016) Chemicals, electricity and fuels from biorefineries processing Brazil's sugarcane bagasse: production recipes and minimum selling prices. *Renew Sust Energ Rev* 53:1443–1458. <https://doi.org/10.1016/j.rser.2015.09.069>
- Smith R, Linnhoff B (1988) The design of separators in the context of overall processes. *Chem Eng Res Des* 66:195–228
- Sreepathi BK, Rangaiah GP (2014) Review of heat exchanger network retrofitting methodologies and their applications. *Ind Eng Chem Res* 53:11205–11220

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