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RESEARCH ARTICLE OPEN ACCESS

ASSESSMENT OF THE POTENTIAL FOR ENERGY RECOVERY IN A SUGAR CANE MILL

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ABSTRACT

One of the problems identified in the sugar industry is the poor management of science and innovation. This paper aims to identify potential energy and water savings and opportunities to improve thermal efficiency in a sugar cane mill using energy analysis and heat integration methods. Methods of energy analysis and pinch analysis are applied using Aspen Energy Analyzer. The establishment of 10 energy performance indicators, which are not currently reported for this industry, will help to define an energy baseline and systematically measure efficiency in the industry. The current hot and cold supply requirements are not met for a minimum allowable temperature difference of 10°C. The design of the heat exchanger network allows 52.23% of the maximum recoverable energy to be recovered. There is a high excess of the current hot supply duty over the minimum hot duty, behaviour associated with the data extraction system. This study will allow us to continue the research with new heat exchangers and full inter-plant integration.

I. INTRODUCTION

The main internal problems identified that correspond to the industry are: (1) poor valuation of by-products and derivatives, (2) high obsolescence and poor technical condition of agro-industrial machinery, especially in the energy base, (3) insufficient management and lack of management models that ensure economic efficiency, quality and safety, non-compliance with technologies established in technical directives, (4) insufficient use of automation and computerisation, and (5) insufficient management of science and innovation, insufficient preparation and motivation of personnel.

The current energy base of the sugar factory has technological deficiencies in steam generation with high biomass and water consumption, which causes instability of the operating parameters of the primary equipment and at the same time increases steam consumption and molasses quality parameters.

There are also objective barriers that limit the use of SEC for energy performance assessment, such as training in energy management and the perception of the economic benefits of identifying energy savings potential in industries. The relevance of the research is given by its contribution to the definition of current SEC, energy targets and energy recovery potential, which are rarely expressed.

The study aims to identify the potential energy and water savings and opportunities to improve thermal efficiency in a sugar cane mill by applying energy use analysis and heat integration methods.

II. THEORETICAL REFERENCE

II.1 SPECIFIC ENERGY CONSUMPTION AND ENERGY RECOVERY

Specific energy consumption (SEC) is often used as an energy performance indicator to evaluate or measure energy efficiency performance, both in the literature and in international standards. Although several research studies have adopted SEC as an indicator of progress towards improved energy efficiency, publications on critical assessments of the use of SEC are scarce. In general, SEC is calculated by dividing the amount of energy used by the amount of products. However, both products and energy sources are often chosen arbitrarily, depending on the purpose of using SEC. For example, SEC can be calculated for the total amount of products or for individual products from the product mix. Similarly, SEC can be calculated for the total primary energy used or for specific energy sources, e.g. how much electricity and heat were used separately to produce a unit of product [1].

The integrated production of first and second generation ethanol from sugarcane is expected to increase the sustainability of the sugarcane production plant, improving its economic and environmental impact as well as the energy efficiency of the whole process. Sugarcane is used to produce sugar, ethanol and electricity. In addition, sugarcane biomass power plants have some advantages over conventional power plants, which are currently based on hydroelectric power generation: faster construction, lower operational risks and costs, and easier environmental licensing.

Electricity is expected to become as important a product in the sugarcane sector as ethanol and sugar [2]. Many graphical and mathematical techniques have been developed for the efficient design of new and retrofitted energy systems. Process Integration (PI) has been used extensively to increase the energy efficiency of processing systems.

The technique, also known as Pinch Analysis (PA), was first introduced to analyse energy flows in process heat exchanger networks based on the second law of thermodynamics [3]. PI focuses on the unity of the process, rather than optimising each process separately, and in turn maximises the resource use efficiency of the industry [4].

Retrofitting a sugar mill's cogeneration unit for the purpose of surplus electricity production may not always be feasible due to, among other things, the seasonality of sugar cane production and the higher costs associated with modern equipment. Given the lower cost of producing electricity from bagasse than from other energy sources, there should be a clear motivation to produce electricity from sugarcane for export to the national grid [5].

A study applied pinch technology to a sugar production process to calculate minimum energy targets [6], where the juice from each evaporation stage is considered as hot streams, but these streams reduce their temperature by vacuum action and not by cooling, therefore the minimum cooling requirement is high. These are soft streams and should not be used for PA. Heat exchanger networks (HENs) have been widely used for energy recovery in process industries.

However, the flexibility problem has usually been ignored in the design of HENs, so they lack sufficient ability to cope with process variations. On the other hand, the synthesis of inter-plant HENs has received increasing attention in recent years due to its potential for overall site energy savings [7]. Intermediates play an important role in indirect inter-plant heat integration. Each of them has a unique performance in heat recovery, but they are rarely used together, which simplifies the problem but limits the extent of heat recovery [8].

III. MATERIALS AND METHODS

Energy management in the paper manufacturing process is based on the Cuban standard ISO 50001: 2019 and a methodology for energy use [9]. Energy Performance Indicators (EnPIs) are determined by applying energy analysis and heat integration. The pinch analysis methodology is used to determine network targets, minimum temperature difference and maximum energy recovery (MER) [10].

Data processing was carried out using Aspen Energy Analyser [11]. The main activities carried out in the energy audit were: (1) analysis of current energy use and consumption, (2) current and minimum energy obligations. The study also includes (3) the identification of energy resource savings to improve energy recovery for the subsequent estimation of economic feasibility.

IV. RESULTS AND DISCUSSIONS

The sugar mill has a crushing capacity of 2,700 t/d. The steam supply consists of a water tube boiler with a superheated steam generation capacity of 60 t/h at 1.34 MPa and 318 ºC, which consumes bagasse. The superheated steam at 1.34 MPa is consumed by 2 backpressure turbogenerators of 1.5 MW and 2.5 MW. The exhaust steam at 0.218 MPa is consumed by the first-effect evaporator in a four-effect evaporator system. Juice heaters consume vapours from the first and second effect evaporators. An alcohol distillery near the sugar mill consumes the molasses, juices and steam from the first-effect evaporator.

Contaminated condensate is recovered for technological use in the evaporators, heaters and tanks. For the energy diagnosis, the current consumption (at least three months) of raw materials, energy resources (electricity, water) and production is recorded and analysed. Mass and energy balances are provided, as well as juice flow, steam consumption, thermal power and evaporator vapour flows, which are essential heat and mass flows for estimating energy performance indicators (EnPIs) or SEC, also for applying the pinch analysis method.

Table 1 shows the results of the steam, heat and water balances in the sugar cane mill, expressed in terms of energy performance indicators.

Tabla 1: Energy performance indicators

Parameters	Value
Specific steam consumption, t steam / t cane	0.48
Specific steam consumption, t steam / t bagasse	2.23
Low pressure steam consumption% cane	35.74
Specific steam consumption in turbogenerators, t / MWh	13.95
Specific bagasse consumption,t / MWh	6.23
Electricity generation, kWh / t cane	34.66
Specific thermal energy consumption,MJ / t cane	1,490
Water make-up, %	26.1
Heat Losses, %	21.0
Thermal efficiency, %	79.0
Steam duty, t/h	54
Thermal power, MW	46.6

Source: Authors, (2025).

Figure 1 shows the process flow sheet and the data for the streams presented in Table 2. The streams considered in the analysis are: Steam to heater (H1); Steam to heater 2 (H2); Steam to heater 3 (H3); Vapour to heater 4 (H4); Vapour from 4th effect (H5); Vapour from pan 1 (H6); Raw juice to heater 1 (C1); Raw juice to heater 2 (C2); Raw juice to heater 3 (C3); Clear juice to evaporator (C4); Thin juice from 1st effect (C5); Condensate from 1st effect (C6); Steam (S); Cooling water (CW).

The process equipment is: heaters (1-4), evaporators (I - IV), pan I (PI). Other parameters are specific heat capacity (cp); heat capacity flow rate (CP); inlet temperature (Ti); outlet temperature (To); film heat transfer coefficient (h) and heat load (ΔH). Vapour properties are calculated for 0.2 MPa.

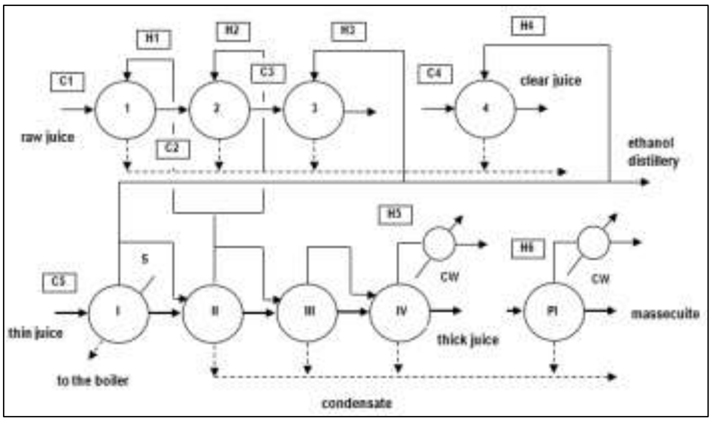

Figure 1: Process flow sheet.
Source: Authors, (2025)

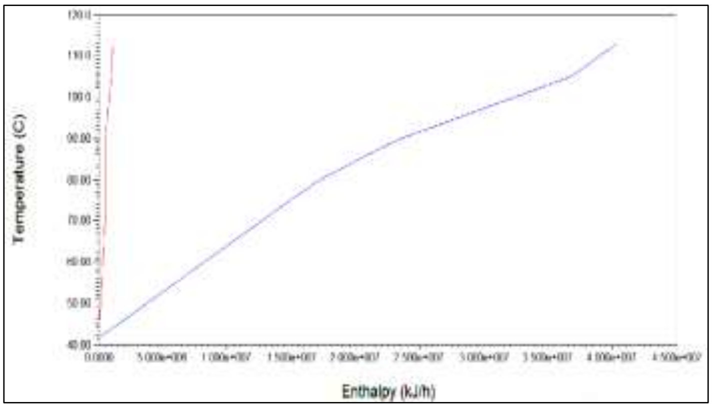

Figure 2: Composite curve diagram.
Source: Authors, (2025).

The global minimum temperature difference (ΔTmin) in this case is set at 10 °C, as this is the minimum temperature difference between the process streams. There is a pinch point at 47 ºC, with a hot and cold pinch at 5 ºC and 42 ºC. The minimum hot and cold loads are 39,240,000 kJ/h and 143,800 kJ/h respectively. The composite curves in Figure 2 show the minimum hot and cold duties. There is an energy potential (MER) of 905,941 kJ/h that can be recovered.

Table 2: Stream data.

Stream	Ti (ºC)	To (ºC)	m (kg/h)		cp (kJ/ kgºC	CP=m·cp (kJ/hºC)
H1	105	90	6,54		1.88	12,302.72
H2	105	90	2,58		1.88	4,846.64
H3	112	90	3,39		1.88	6,380.72
H4	112	90	3,35		1.88	6,298
H5	70	45	3,93		1.88	7,382.76
H6	70	45	7,00		1.88	13,160
C1	42	75	116,86		3.84	448,746.24
C2	75	88	116,86		3.84	448,746.24
C3	88	105	116,86		3.84	448,746.24
C4	90	107	115,32		3.84	442,855.68
C5	107	113	115,32		3.84	442,855.68
C6	80	90	40,21		4.19	168,479.9

Source: Authors, (2025).

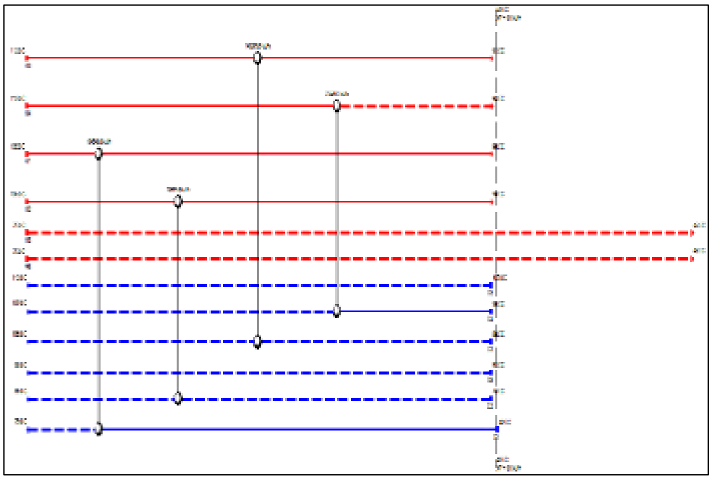

Figure 3: HEN Design.
Source: Authors, (2025).

Figure 3 shows the position of the heat exchangers in the feasible combinations. According to the flow splitting algorithms, above the pinch the number of hot flows (Nh) must be less than or equal to the number of cold flows (Nc) and it is verified that all combinations above the pinch are feasible (CPh ≤ CPc). Table 3 shows the heat exchanger data as a result of the HEN design.

Table 3: Heat Exchangers data.

HeatExchanger	Cold Stream	Ti (°C)	To (°C)	Hot Stream	Ti (°C)	To (°C)	Load (kj/h)	Area (m$^{2)}$	Tmin Cold (°C)	Tmin Hot (°C)
E-100	C1	42	42.41	H1	105	90	184.541	0.52	62.58	48
E-101	C2	42.41	42.57	H2	105	90	72.699.6	0.20	62.42	47.59
E-102	C3	42.47	42.78	H3	112	90	140,376	0.37	69.21	47.53
E-103	C4	90	90.17	H4	112	100	75,576	0.77	21.82	10

Source: Authors, (2025).

As can be seen in Table 3, the cold streams do not reach the outlet temperatures due to the limitations of the method that considers sensible heat. This assumption results in high temperature differences at the hot and cold ends, smaller heat transfer areas and lower heat recovery, but avoids violations of the second law of thermodynamics. The modified design of the heat recovery network allows 52.23% of the maximum energy recovery to be recovered. The current hot utility of 167,760,000 kJ/h, shown in Table 1, is far from the minimum hot utility.

A fuel net calorific value of 43,157 kJ/kg, 150 days of operation per year (crushing season), 20 hours per day and a fuel (FO) price of $512.9/t are assumed. The four heat exchangers provide annual savings of 39.6 tonnes and $20,310 /year in fuel costs.

V. CONCLUSIONS

The establishment of 10 energy performance indicators, which are not currently reported for this industry, will help to define an energy baseline and systematically measure efficiency in the industry. The current hot and cold supply requirements are not met for a minimum allowable temperature difference of 10°C. The design of the heat exchanger network allows 52.23% of the maximum recoverable energy to be recovered. There is a high excess of the current hot supply duty over the minimum hot duty, behaviour associated with the data extraction system. This study will allow us to continue the research with new heat exchangers and full inter-plant integration.

VI. AUTHOR’S CONTRIBUTION

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Investigation: Jorge Guevara Rodríguez, Juan Pedro Hernández Touset, Lirianet Fuentes Ramírez.
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Approval of the final text: Jorge Guevara Rodríguez, Juan Pedro Hernández Touset, Lirianet Fuentes Ramírez.

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