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Article of investigation

Estimation of the potential for electrical energy savings in a sugar factory

Estimación del potencial de ahorro de energía eléctrica en una fábrica de azúcar

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Palabras clave: eficiencia energética, índice de desempeño energético, potenciales de ahorro energético, línea base de consumo de energía.

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Abstract

The purpose of this study is to present the application of energy management tools to carry out an energy characterization of a sugar mill. This research work was carried out within the framework of a national industrial project, which received funding from the United Nations Industrial Development Organization (UNIDO). The project was specifically aimed at small and medium-sized companies (SMEs) in the industrial sector of Valle del Cauca, with the objective of establishing management tools to measure energy performance and achieve sustainable improvements over time. Within the scope of this study, we were able to identify significant energy uses, called significant variables. Furthermore, we define the energy baseline, goal line, and consumption rate. In addition, critical indicators of production value, savings potential and performance were determined. Recommendations were also provided to improve the company's energy performance. Consequently, we calculated the savings potentials for the different levels of production at sugar mill, which translated into an energy saving of 1,105,537 kWh for the year 2021. This is equivalent to an economic cost of $ 397,993,454.

Resumen

El propósito de este estudio es presentar la aplicación de herramientas de gestión energética para llevar a cabo una caracterización energética de un Ingenio. Este trabajo de investigación se llevó a cabo en el marco de un proyecto industrial nacional, que recibió financiamiento de la Organización de las Naciones Unidas para el Desarrollo Industrial (ONUDI). El proyecto se dirigió específicamente a las pequeñas y medianas empresas (PYMES) del sector industrial del Valle del Cauca, con el objetivo de establecer herramientas de gestión para medir el desempeño energético y lograr mejoras sostenibles a lo largo del tiempo. Dentro del alcance de este estudio, pudimos identificar los usos significativos de energía, denominados variables significativas. Además, definimos la línea base de energía, la línea de meta y el índice de consumo. Además, se determinaron los indicadores críticos del valor de producción, el potencial de ahorro y el rendimiento. También se proporcionaron recomendaciones para mejorar el rendimiento energético de la empresa. En consecuencia, calculamos los potenciales de ahorro para los diferentes niveles de producción en el Ingenio, lo que se tradujo en un ahorro de energía de 1105537 kWh para el año 2021. Esto equivale a un costo económico de $ 397993454.

Why was it carried out?

The Universidad Autonoma de Occidente, the Universidad Autónoma de Bucaramanga and the Universidad del Atlántico, were selected to lead the implementation of the Industrial Evaluation Center, CEI, within the framework of the Industrial Evaluation Program, PEVI, and support the improvement of the energy performance of the national productive sector.

For this stage, the UAO, through the UAO/PEVI Industrial Evaluation Center, will advise aminimum of 10 companies in Valle del Cauca to improve their energy performance through energy management. One of the selected companies was Ingenio del Cauca (Incauca S.A.) where energy management was implemented as part of the PEVI program.

What were the most relevant results?

The energy study was applied to obtaining sugar and its derivatives at Ingenio del Cauca S.A.

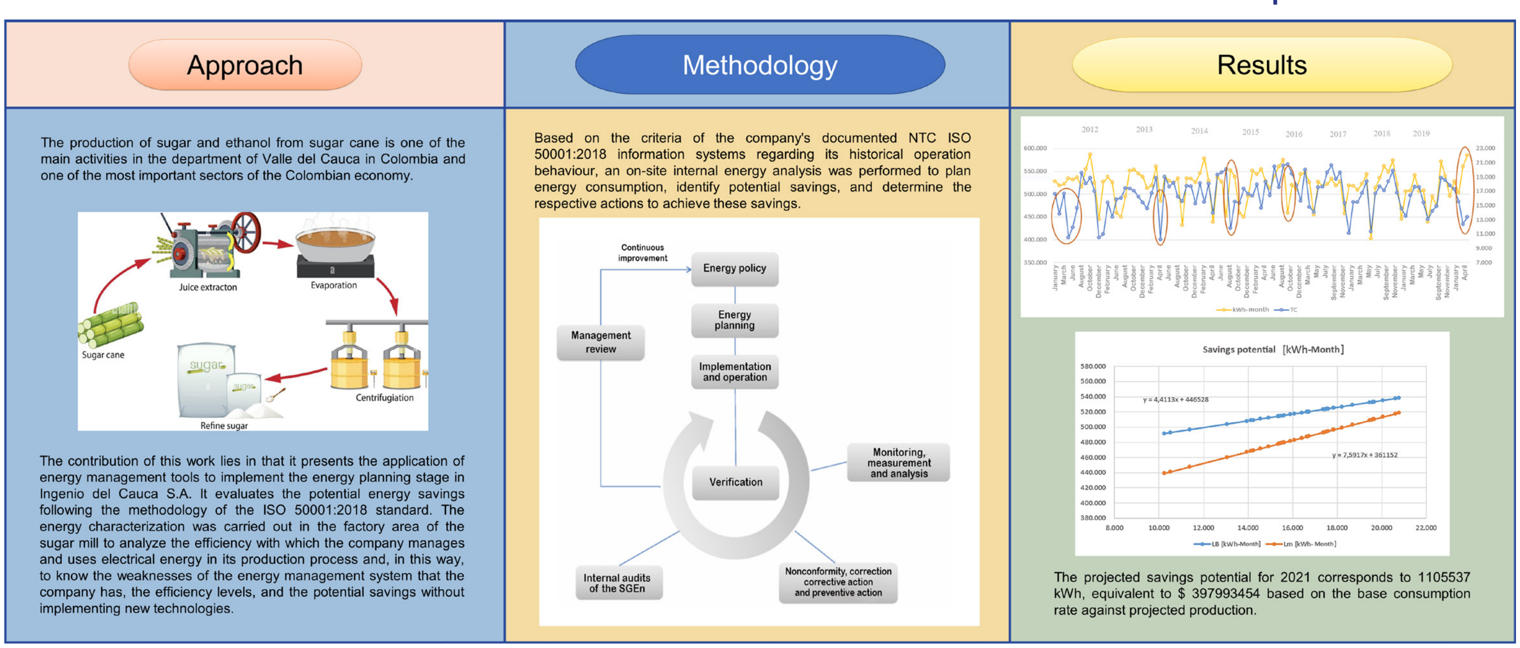
The data on raw material processed and energy consumption between January 2012 and April 2020 were analyzed to establish improvement options that can be applied to optimize the plant's operation. The P-value analysis allows us to establish that the significant variable is the tons of cane and is the one that has the greatest impact on energy consumption. According to the results obtained, the variable to be evaluated is the amount of cane processed in units of tons. By establishing baseline and target lines for energy consumption based on the amount of sugarcane processed, the study calculated potential energy savings by comparing actual consumption with the target line. This analysis provided insights into opportunities for optimizing energy usage in the sugar production process. Using historical data, the amount of raw material processed [tons] and kWh energy consumption for the year 2021 was averaged month by month, and the values were determined. Next, the base CI of the best production month was identified, whose value was 25.9 kWh/TC, an index with which the new theoretical energy consumption for 2021 was projected, and the savings potential was calculated. The projected savings for 2021 are in the order of $ 397'993,454.

What do these results provide?

The results from the study on estimating energy potential savings in a sugar factory provide several valuable insights and benefits:

1. Energy Efficiency Improvement: By identifying significant energy uses and analyzing energy consumption patterns, the study offers opportunities for improving energy efficiency in sugar production processes. This can lead to cost savings, reduced energy consumption, and enhanced sustainability.
2. Operational Optimization: The analysis of energy consumption in relation to the amount of raw material processed highlights areas where operational optimization can lead to energy savings. This information can guide decision-making and resource allocation to improve overall efficiency.
3. Target Setting: Establishing baseline and target lines for energy consumption based on production levels allows for setting specific targets for energy savings. This provides a roadmap for implementing energy management strategies and monitoring progress towards achieving efficiency goals.

Graphical Abstract



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Introduction

Industry currently consumes 31% of all energy generated worldwide, and about 67% of electricity is generated from fossil fuels. This panorama places the industrial sector, directly or indirectly, as one of the most polluting sectors of the environment. However, it is related to a high potential for energy savings and emissions since, for a scenario of sustainable development in 2050, energy efficiency can reduce CO2 emissions by 37% (1) (2).

In recent years, energy efficiency has been a topic of great interest for companies due to the need to reduce production costs and increase their competitiveness, as well as because it has a positive impact on the environment by reducing CO_2 emissions (3)-(6). The energy performance of industrial processes can be increased through technological change measures and implementing an energy management system. Thus, the great impact of energy management systems in improving energy efficiency and reducing CO_2 emissions led to the development of ISO 50001 with the support of UNIDO (7). The first version of ISO 50001: Energy Management Systems was issued in 2011, and the second version in 2018 (8).

Estimating the carbon footprint of raw and refined sugar production has been identified as an important aspect of sustainable production. Different countries and plants have reported other carbon footprints, and some have achieved lower emissions by selling electricity and using renewable fuel sources. The need for factories to demonstrate sustainable practices has led to sustainability performance reporting based on guidelines proposed by the Global Reporting Initiative and accreditation to ISO 14001 for environmental management (17). Also, the sustainability practices of companies in the Brazilian sugarcane sector participating in the Clean Development Mechanism (CDM) are identified, and their association with financial performance is investigated. The results indicate that the industry's most commonly performed sustainability practices are reducing sugarcane burning and CO_2 emissions, preserving or restoring natural areas, and generating electricity (18). The sugarcane ethanol industry in Brazil has demonstrated a commitment to sustainability through the use of voluntary standards, codes of conduct, and corporate social responsibility practices, particularly in the state of Minas Gerais, and has received significant foreign investment for its expansion, indicating strong international interest (19)(20).

Sugarcane and ethanol companies in Brazil have sought Management System Standard certification to become more attractive in international markets and facilitate the export process, particularly to the European Union and Asia. The structure of preference for certifications in the Brazilian sugarcane supply chain shows a greater preference for suppliers with ISO 9001, ISO 22000, ISO 14001, OHSAS 18001, and ISO 27001 certifications (21). Gutierrez et al. (22) propose a methodology for the energy evaluation of a sugar mill's evaporation station, complementing existing energy management methods in sugar mills. It also involves planning the necessary resources and time, collecting experimental operating data, reviewing and calibrating measuring instruments, and applying the recommendations for planning energy audits established in ISO 50002. Hernandez et al. (23) propose an optimized thermal scheme for the mill, including the replacement of generators and rehabilitation of insulation, which will result in better efficiency indicators such as the amount of bagasse left over and electricity generation.

On the other hand, Mary et al. (24) found several implications for companies in the agroindustrial sector, particularly those involved in the production and management of sugarcane energy in Brazil. Da Silva Souza et al. (25) present an index to evaluate

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the environmental performance of the sugar energy industrial process in their study, considering the residues generated in manufacturing operations. This index can be used as a tool to guide companies towards better environmental and waste management practices.

Implementing energy efficiency measures is a key low-cost practice. These measures can include simple but effective actions, such as optimizing equipment start-up procedures, performing proactive maintenance to ensure that equipment operates at maximum efficiency, and implementing soft starters to reduce machinery starting currents (26).

It is important to consider the quantity and quality of energy for better utilization of energy resources in sugar production processes. Exergetic analysis can be very relevant to estimating the second law efficiencies in the different components of a production plant (9). Also, the modern agricultural system requires a higher energy input than the traditional one. Energy is used directly in the operations of tillage, planting, and harvesting and indirectly in inputs such as pesticides, fertilizers, transportation, drainage construction, and other inputs associated with sugar production (10). These different operations provide opportunities for energy savings. Although the mills have a great opportunity to contribute to the supply of the Colombian electricity market, their processes could be more efficient due to the use of very old technologies; therefore, studying them to improve them is important.

According to Cenicaña 2015, in Colombia, the government has been encouraging the use of cogeneration of energy from biomass through some decrees of law that allow income exemption for those who sell electricity from these practices. Additionally, it can be mentioned that the country has great potential to develop a cogeneration industry based on sugar cane bagasse. In (11), different cogeneration system options in sugar cane mills are analyzed to evaluate the possibilities of increasing electricity generation. There is a case on the sugar industry and the economics for the advanced cogeneration energy system is elaborated, where the replacement of low-efficiency mill turbines with hydraulic drives and direct current motors, the cogeneration power increases in the sugar mills to operate with high efficiency (65-70%). This replacement helps to increase power generation, which leads to additional income at the sugar mill (12). To date, of the 21 cogeneration plants existing in Colombia, 11 correspond to sugar mills: Risaralda, Riopaila, San Carlos, Providencia, Manuelita, La Cabaña, Castilla, María Luisa, Mayagüez, Incauca and Bioenergy. Figure 1 shows an annual report from Asocaña where the installed cogeneration capacity of the mills from 2010 to 2018 and how it has increased from 173.7 MW to 316.2 MW, respectively.

Cogeneration and Surplus 2010-2018

Year	Installed Cogeneration Capacity (MW)	Installed Surplus Capacity (MW)	Cogenerate Electrical Energy (MWh)	Sale of Surplus to the SIN (MWh)
2010	173,7	45,8	nd	nd
2011	180,0	52,9	nd	nd
2012	182,0	52,9	nd	nd
2013	186,5	50,5	1.091.090	349.244
2014	214,5	68,1	1.296.921	441.219
2015	236,5	78,1	1.380.948	513.843
2016	253,0	93,6	1.417.560	591.717
2017	306,2	119,6	1.555.960	622.218
2018	316,2	127,6	1.702.236	726.153

Figure 1. ASOCAÑA anual report 2018-2019.

Energy Management Systems have proven their success as a methodology to improve companies' energy performance, regardless of their size or activity. Given that the expenses associated with energy use represent an important part of companies'

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operating costs, it is evident that a reduction in these costs contributes significantly to their competitiveness. The contribution of this work lies in that it presents the application of energy management tools to implement the energy planning stage in Ingenio del Cauca S.A. Finally, it evaluates the potential energy savings following the methodology of the ISO 50001:2018 standard. In this work specifically, the energy characterization was carried out in the factory area of the sugar mill to analyze the efficiency with which the company manages and uses electrical energy in its production process and, in this way, to know the weaknesses of the energy management system that the company has, the efficiency levels, and the potential savings without implementing new technologies. This mill, where this procedure was implemented, participated in the Industrial Evaluation Program (PEVI) and is located north of the department of Cauca, Colombia.

Methodology

Based on the criteria of the company's documented NTC ISO 50001:2018 information systems regarding its historical operation behavior, an on-site internal energy analysis was performed to plan energy consumption, identify potential savings, and determine the respective actions to achieve these savings (13)-(16). This International Standard is based on the continuous improvement cycle Plan-Do-Check-Act (PDCA) and incorporates energy management into the organization's usual practices, as illustrated in Figure 2.

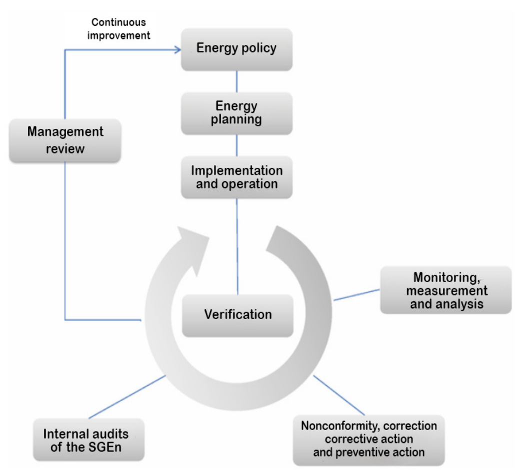

Figure 2. Continuous improvement cycle.

In the context of energy management, the PDCA approach can be summarized as follows:

Plan: Conduct the energy review and establish the baseline, energy performance indicators, objectives, targets, and action plans necessary to achieve the results that will improve energy performance by the organization's energy policy. Figure 3 provides a schematic view of this phase.

Do: implement energy manegement action plans.

Verify: monitor and measure processes and key characteristics of operations that determine energy performance in relation to energy policies and objectives and report the results. Act: take actions to continuously improve energy performance and the Energy Management System.

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Energy Planning is the basis for implementing an energy management system according to ISO 50001:2018; this work follows the methodology shown in Figure 3. It should be clarified that this work will address the tactical component of energy planning.

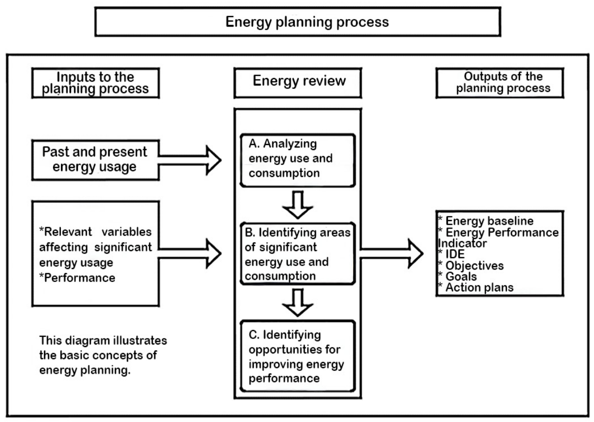

Figure 3. Energy planning.

Results and discussion

The energy study was applied to obtaining sugar and its derivatives at Ingenio del Cauca S.A. The data on raw material processed and energy consumption between January 2012 and April 2020 were analyzed to establish improvement options that can be applied to optimize the plant's operation.
Figure 4 shows the behavior of the amount of raw material processed, for which it has been decided to use as a unit the tons of cane TC instead of kilograms kg since it is commonly used in sugar mills, and the monthly energy consumption kWh in the period from 2012 to 2020 for the process of obtaining sugar and its derivatives.

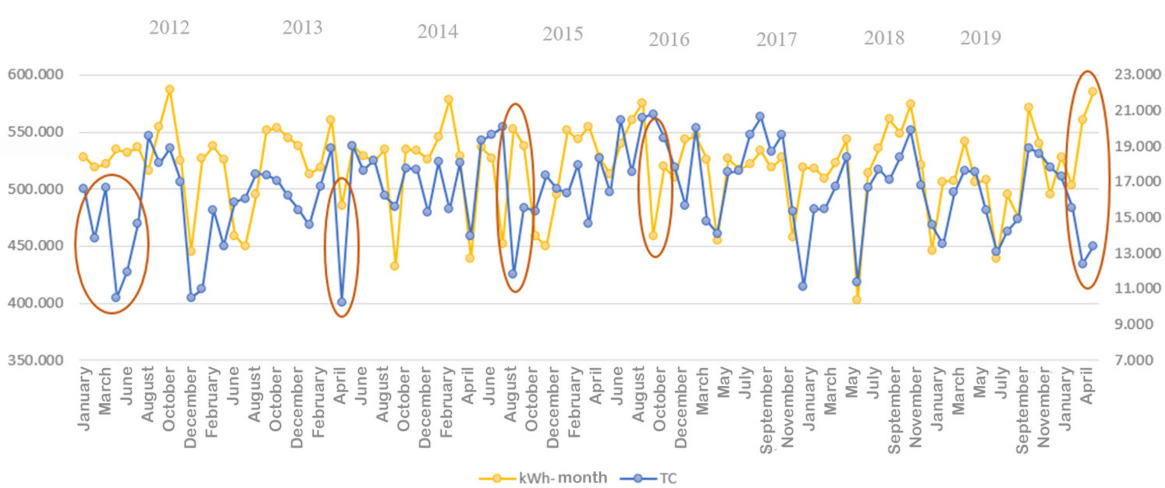

Figure 4. Energy consumption analysis.

It can be established that the behavior of both parameters shows a predominantly linear correlation, so that as the amount of raw material processed increases, so does the energy consumption. However, it was found that for February, April, May, June, July, and December 2012, the energy consumed by the raw material processed is much higher than the average, with values of 16455 tons of cane and 519114 kWh in energy consumption, which represents an opportunity for improvement through an energy management system. This same behavior is presented in different months of

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subsequent years, thus creating the need to analyze why the predominantly linear trend was not maintained and propose alternatives to improve the correlation of the two parameters. The red ovals highlight the months with the highest energy consumption and the lowest cane processing, indicating low efficiency in the production process and representing opportunities for improvement.

Figure 5 shows the Sankey diagram for part of the cogeneration process at Ingenio del Cauca. From the consumption data at the different points of the factory, it can be seen that the milling process demands 30% of the electrical power generated (840 kW) by cogeneration, 45% (1260 kW) goes to the substation and 17% (476 kW) to processes in the factory. It can be seen that in these processes, there is an opportunity for improvement in the use of the electrical power generated by cogeneration, which corresponds to 2800 kW, which indicates that the milling part can be optimized by reducing mechanical losses; in addition, the energy losses in the substation and factory processes would have to be reviewed.

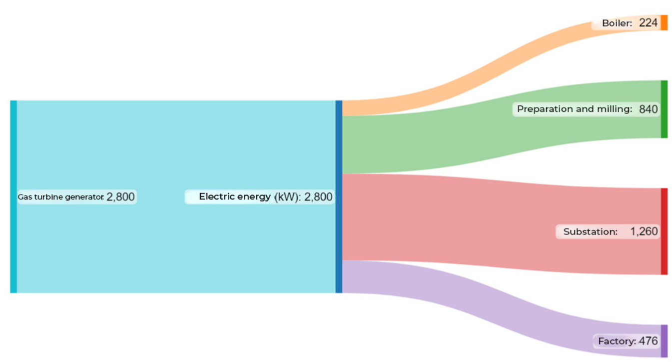

Figure 5. Sankey diagram of energy consumptions.

Energy variables and the company’s operating conditions, technological changes, and maintenance management were evaluated to identify the Significant Energy Uses in obtaining sugar and sugarcane derivatives. Based on the information provided by the company, there is evidence of dispersed operating conditions, which allows us to identify that there are no standardized operating and maintenance procedures, which represents an opportunity for improvement.

The following variables were evaluated for the case study: quantity of cane processed, quantity of cane fiber, water consumption, steam mass flow rate used in the process.

Table 1 presents the statistical analysis of the different variables selected in the study to determine which variable has the greatest influence on energy consumption.

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Table 1. Identification of significant energy uses.

	Coefficients	Typical Error	Statistic t	**Probability <0,05**	Lower 95%	Upper 95%	Lower 95,0%	Upper 95,0%
Amount of processed sugarcane [Ton/h]	9,1890	3,4049	2,6987	**0,0082**	2,4294	15,9487	2,4294	15,9487
Water Comsuption [m^3]	1,0196	0,6054	1,6842	**0,0954**	-0,1823	2,2215	-0,1823	2,2215
Amount of sugarcane fiber [ton]	-2760,5340	4243,8093	-0,6505	0,5169	-11185,560	5664,4927	-11185,5607	5664,4927
Steam mass flow [lb/h]	-0,0019	0,0030	-0,6354	0,5267	-0,0080	0,0041	-0,0080	0,0041

This *P*-value analysis allows us to establish that the significant variable is the tons of cane and is the one that has the greatest impact on energy consumption. According to the results obtained, the variable to be evaluated is the amount of cane processed in units of tons.

The quantity of cane processed and energy consumption were plotted. Figure 6 shows the trend line for which Eq (1) is obtained:

$$E_m = 4{,}4113m + 446528 \qquad R^2 = 0{,}0884 \quad (1)$$

The low correlation factor is associated with the historical data's high dispersion, as shown in Figure 6. Normally, the independent term of the baseline equation represents the amount of energy consumed not associated with the production E_0. However, in the production process analyzed, the milling stage presents an operating lag concerning the rest of the raw material processing stages. In this case, the energy consumption is 446528 kWh per month.

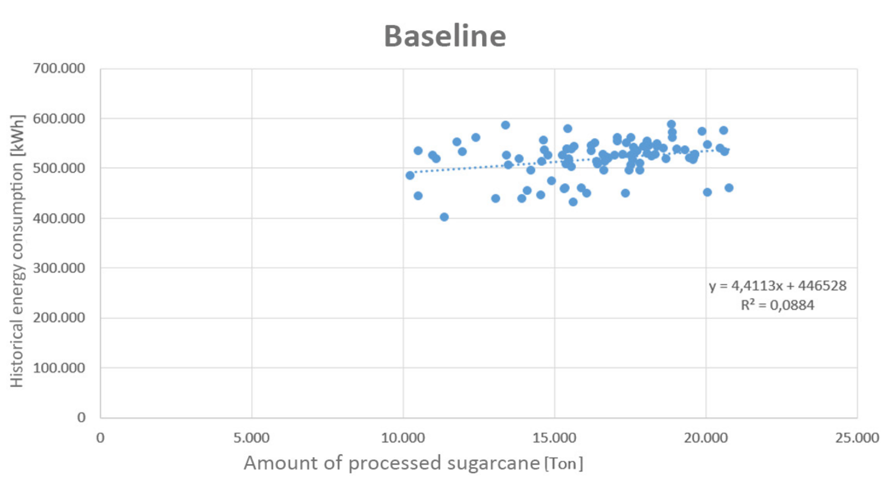

Figure 6. Baseline graph of energy consumption as a function of the amount of sugarcane process.

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Once the baseline was established, the months in which an optimum ratio between raw material processed and energy consumption were evaluated, and that period was used as a reference to develop the target line shown in Figure 7.

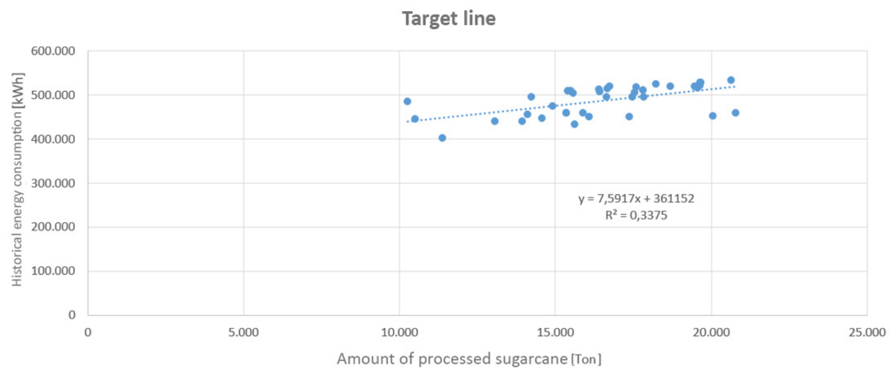

Figure 7. Target line graph of energy consumption as a function of the amount of cane process.

It is possible to determine the potential energy savings by subtracting the target line from the energy baseline and plotting the baseline and target lines previously established on the same graph, as shown in Figure 8.

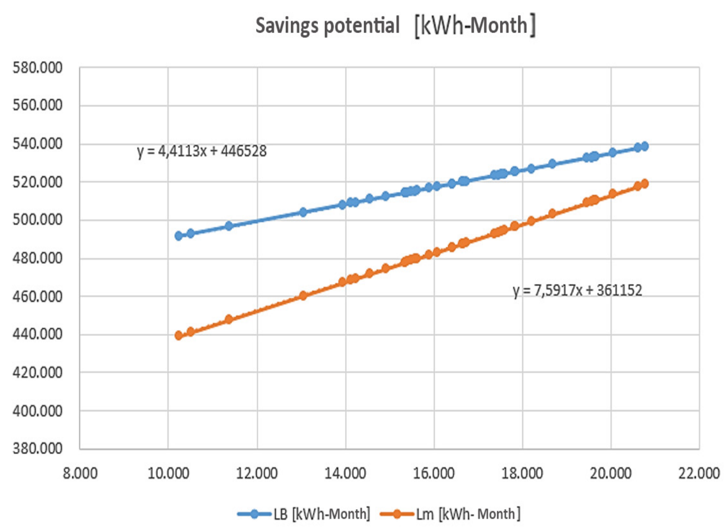

Figura 8. Historical kWh target line graph as a function of historical TC.

Different savings potentials can be obtained according to the historical tons of sugarcane from 2012 to 2020 and the point-to-point differences between the baseline and the target line. An important indicator instituted in this work is the consumption index (CI), through which production management can establish potential energy savings. This consumption index is obtained by dividing the energy baseline by the production P mathematically; it can be written as shown in Eq (2):

$$CI = m + \frac{E_0}{P} \quad (2)$$

The base consumption index is constructed from the linear equation of the correlation of the data of processed sugarcane quantity [tons] and energy consumption [kWh] represented by Eq (1), according to the available information, for each month from 2012 to 2020. This index serves as a reference in comparison with the actual consumption index. If the actual consumption index's value is lower than the base consumption index's value, the operation is efficient; otherwise, the operation is inefficient. According to the study's information and as observed in Figure 9, the consumption

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index shows that the higher the sugarcane processing, the higher the energy consumption index improves substantially.

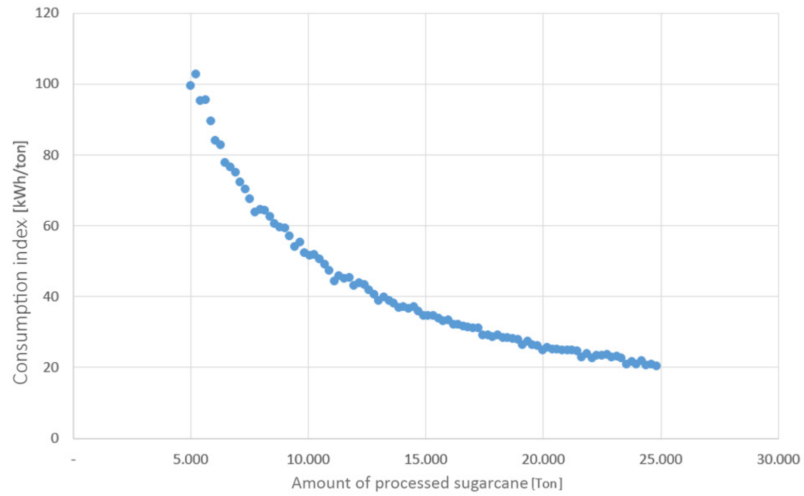

Figura 9. Consumption rate as a function of the amount of cane processed.

Proper production planning implies better energy performance. The knowledge of a critical production, where the increase in production does not significantly affect the CI, is fundamental for such planning. This value is determined with the cumulative sum of the theoretical consumption index (TCI) variation to the production variation, the TCI calculated with the energy baseline equation, and the actual production values. The critical production of the Cauca sugar mill is 16077 tons of sugarcane; this value was found through statistical analysis. Figure 10 shows the inflection point that identifies the critical tons of cane to be processed and divides the high and low energy consumption zones.

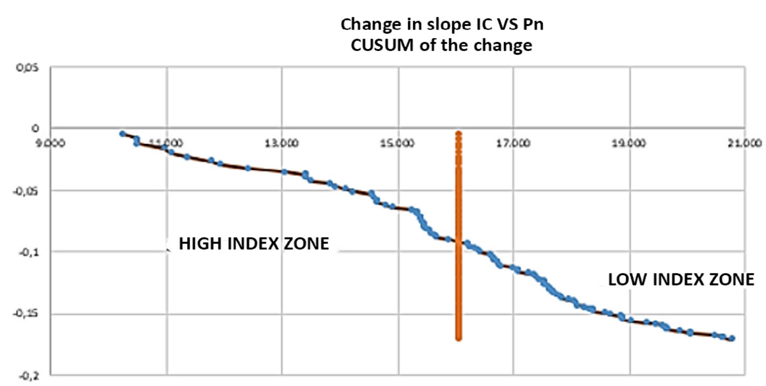

Figure 10. Identification of the critical production of Ingenio del Cauca.

The calculation of the potential is based on determining the energy savings that can be produced by working at lower energy consumption rates with the same monthly production. This saving potential is achieved by increasing the cane processing rate above the identified breakpoint. The consumption rate for 16077 tons of cane was 28 kWh/TC, very close to the base CI value (25.9 kWh/TC), while the average CI was 32.28 kWh/TC. This critical production value associated with the 529 h/month operating time allows us to know the average milling rate of 30.39 tons of cane per hour (TCH), as shown in Figure 11. From this milling rate, the Cauca sugar mill stabilizes from the operational and energy point of view.

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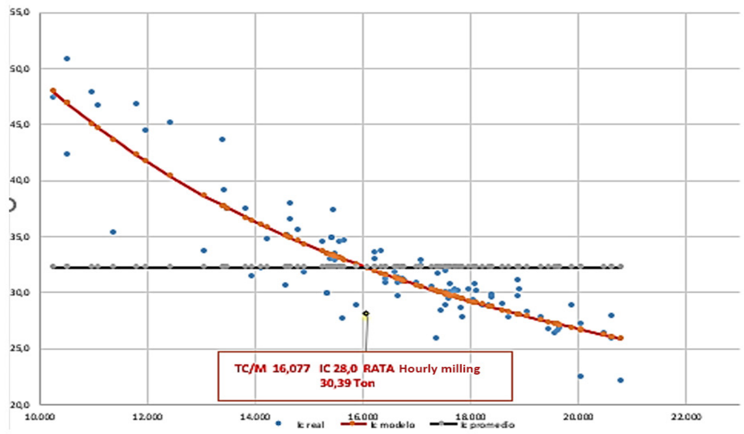

Figure 11. Critical consumption rate as a function of critical production.

Using historical data, the amount of raw material processed [tons] and kWh energy consumption for the year 2021 was averaged month by month, and the values were determined. Next, the base CI of the best production month was identified, whose value was 25.9 kWh/TC, an index with which the new theoretical energy consumption for 2021 was projected, and the savings potential was calculated, as shown in Table 2. The projected savings for 2021 are in the order of $ 397’993,454.

Table 2. Estimated savings potential by the year 2021.

Month	Sugarcane tones Historical Average [ton]	Historical average consumption [kWh/month]	Theoretical consumption [kWh/month]	Historical average consumption [kWh/month]	Savings Potential [kWh/ month]	Savings potential [%]
January	15144	523904	392233	476122	131671	25,13
February	16421	532545	425299	485814	107246	20,14
March	16228	539717	420303	484350	119414	22,13
April	14431	511253	373765	470708	137489	26,89
May	16513	503951	427683	486513	76268	15,13
June	16612	507166	430264	487269	76902	15,16
July	17286	530348	447712	492383	82637	15,58
August	17925	521681	464269	497236	57413	11,01
September	18333	537019	474819	500329	62199	11,58
October	17010	504679	440552	490285	64126	12,71
November	14554	504935	376944	471640	127991	25,35
December	17266	509361	447180	492228	62181	12,20
Overall total	16477	518880	Savings (kWh/month) for 2021		1105537	
			$/kWh		360	
			Savings for 2021 $		397993320	

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The savings opportunities for Ingenio del Cauca are presented below once all the results obtained from the energy management tools have been given.

Energy management by operation: Based on the knowledge that the mills have a lag of about 8 hours in start-ups and shutdowns between the cane milling process and the rest of the plant (cogeneration, manufacturing, and services), it is of vital importance to maintain these time values in standards that are validated for the Cauca sugar mill, which in the linear behavior would be part of the energy consumption not associated with cane milling and represent a significant savings potential. In this direction, the standardization of plant stops and starts is recommended. Time lost due to non-standardized plant operations accounts for 5% of the total.
Maintenance energy management: On the other hand, following up on the maintenance schedule of production equipment is recommended to ensure compliance with machine maintenance times to reduce unscheduled plant downtime, which accounts for about 8% of lost time and generates energy consumption.
General: Energy consumption not associated with sugarcane milling represents 86% of the total energy consumed at the mill. In addition to the operation above and maintenance standardizations, it is recommended that the consumption of other equipment, such as air conditioners, lighting systems, and water wells outside the plant, be monitored.
Administrative: It is important that all personnel performing activities within the Mill's facilities become aware of the efficient use of energy by implementing good practices, such as turning off lighting, computer equipment, and air conditioning whenever they leave the premises at the end of the workday.

Conclusions

The projected savings potential for 2021 corresponds to 1105537 kWh, equivalent to $ 397993454 based on the base consumption rate against projected production.

The projected savings values can be reached or achieved as soon as Ingenio del Cauca S.A. implements the energy management system to accurately and effectively analyze and identify the causes of the periods in which the operation is inefficient.

With the implementation of the Energy Management System would come the standardization of operations and maintenance of the plant, in addition to the awareness of the efficient use of energy by the personnel.

The critical production of 16077 tons of cane per month (30.39 tons/h) was the point at which the plant's operation improved its energy consumption performance indicators.

The Cauca sugar mill's average consumption index is 32 kWh/ton of cane; however, the baseline shows a consumption index of 25.9 kWh/ton of cane as the best performance achieved. Between these two values is located the IC of 28 kWh/ton of cane, corresponding to the critical production. Establishing an initial goal to reach the critical point on average would be the first objective to get the best performance point.

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