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Energy audit of a sugarcane plant to find out the main energy saving opportunities

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Abstract

Sugar extraction from sugarcane/sugar-beet is an energy-intensive process, both thermal and electrical energies. However, there are numerous opportunities for energy efficiency improvements. A number of tests were conducted in an old sugarcane factory, including the boiler, electricity generation, process, and mill section, to better understand these opportunities. During four years, specific energy consumption was 16-28 GJ/ton of raw sugar. Measurements and calculations revealed that some equipment, e.g. shredder's steam turbine and some gearboxes, require extensive repairs. The second set of areas for improvement relates to proper operation, such as determining the boiler excess air (which results in an average 0.6% efficiency reduction) and factory planning (near 200 MWh per year). The third type of improvement is to modify or integrate new elements into the existing plant, like water storage tank insulation (3.8 MW) and switching from load-unload operation to drive control for instrumentation compressors (43 MWh).

Keywords: Energy efficiency; Sugar; Thermal energy; Waste energy; Steam turbine

Introduction

An effective tool to assess a plant's current energy-related conditions is an energy audit. A regular practice in many industries is to perform an energy audit every 3 to 5 years. In some circumstances, an annual energy audit is acceptable, but longer than every five years is not recommended. An industrial energy audit has several benefits, such as reducing emissions, costs, and energy consumption.It may also help to improve process organization (Kluczek and Olszewski, 2017). The pulp and paper (Boharb *et al.* 2017; Klugman *et al.* 2007), cement (Engin and Ari, 2005), and clothing (Çay, 2018) industries are just a few that could benefit from the energy audit.

In sugarcane and sugar beet factories, there are a plenty of energy consuming equipment for extracting sugar from sugarcane and sugar beet. These two types of crops go through a similar process, particularly after the sugar is turned into syrup. So, we looked for the energy audit activities in the literature for both cases. Numerous studies have been done based on the amount of energy used in the agricultural section of a sugar beet or sugarcane factory. For example, by gathering data from 146 sugar beet farms, it was found that the energy consumption per hectare is close to 40,000 MJ in Turkey (Erdal *et al.* 2007). This article also showed that any decrease in energy consumption is crucial because the profit to cost ratio of these farms is typically very close to one (~ 1.17). Nevertheless, the main focus of the current study is on the process part of a sugar factory, not agricultural part.

Many research on process plants of sugar factories focused on calculations relating to multi effect evaporators, such as (Chantasiriwan, 2019). In some other articles, such as (Taner and Sivrioglu, 2015), the energy or/and exergy efficiencies of sugar factories have been calculated based on thermodynamics calculations.

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These kinds or research mainly aim to find the effectiveness of a process plant and then suggest a modification in design parameters or configuration of the plant. Some other authors have studied sugarcane plants only from an energy viewpoint with less Thermodynamics calculations. Reviewing the sugar plants in India, the steam consumption mass was in the range of 26-45% of the input cane (Rao and Naqaraian, 2012). The authors suggested some saving opportunities for electrical and thermal energies. Energy required for sugarcane milling was estimated to be 1.95 GJ per ton of cane (Mendoza and Samson, 2002). In addition, some authors only paid attention to one or two items. For instance, potential of replacing the electrical motors in a sugarcane factory with energy efficient motors was discussed (Soppimath and Hudedmani, 2017). In another energy audit, motors' electrical power was measured (Gunness *et al.* 2007) with the suggestion that their power factor need to be improved.

Apart from energy audit activities, many literatures deal with using the by-products of the process (e.g. molasses and bagasses) as alternative fuels (Cortez *et al.* 2020; Hofsetz and Silva, 2012). This approach could be seen more among Brazilian researchers while the largestproducers of Ethanol worldwide are US and Brazil (Renewable Fuels Association, 2015) and Brazil uses sugar beet to make Ethanol. Based on a study, for producing Bio-Ethanol the best option is to use sugarcane. Sugar beet ethanol is also more attractive compared to corn Ethanol by considering energy demand and economical indicators (Manochio *et al.* 2017).

In this study, the focus was on measurements of a real plant. In contrast to many articles that have focused on sugar plants from thermodynamics viewpoint (Bayrak *et al.* 2003; Taner and Sivrioglu, 2017; Lambert *et al.* 2018; Şahin *et al.* 2010; Dhakar *et al.* 2021), here we pay more attention to individual equipment efficiencies. These measurements were done in a varietyof factory areas, from electrical to mechanical parts. In fact, there isn't muchin the literature about analyzinga real,old sugar factory. We felt the necessity of looking at a sugar plant beyond the thermodynamics calculations which are mainly based on design data. In this regard, the importance of different steam turbines (as prime movers of cutters, mills, etc.), boiler, instrument compressors, electrical energy consumption, body heat loss, and load management were discussed.

Materials and methods

Plant description

Production of raw sugar from sugarcane is about extraction of sucrose from sugarcane crops. The sucrose needs to be dissolved in water first for this to work. The result is referred to as the juice, which has a sucrose content of almost 11% (i.e. Brix of the juice is 11%). To achieve the juice, we need a few mills in series. In the studied plant, sugarcane was first sliced through two rotary cutters. In the following step, the canes pass through a shredder and torn by 88 specialized hammers. Then the sucrose is ready to be extracted from the cells of the cane under pressure and to be mixed with water. This duty is done by five mills in series. Each mill consists of six rollers to press the mixture of water and cane. The water is added to the 5th mill while the mixture will move back from the 5th mill to 4th and then from 4th to 3rd and so on. This will improve the effectiveness of sugar extraction. The final juice exits from 1st mill and the remaining pulp (named bagasse) exits from the 5th mill. The bagasse which consists of 2-2.5% sugar will be exported to a paper factory as the main feed.

Some additives (such as phosphate) will then be added to the juice. There are still a few solid components in the juice that should be removed using centrifugal force in the clarifier where we collect and remove the mud. In the next step, the water content of the juice will be decreased by multi stage evaporation. The outcome, named syrup, has a Brix value equal to 65%. Syrup will pass through a combination of continuous and batch pans where it will be heated to further reduce the water content. The Brix value will be then more than 90%. The main mechanism used in pans is crystallization caused by introducing sugar particles called seed. A few centrifugal equipment will collect the final raw sugar.

From the energy viewpoint, the factory consumes both thermal and electrical energy. The main consumers of the electrical energy are vacuum pumps to attain a negative gage pressure inside the evaporators and pans, instrumental compressors and some small motors of pumps. In the studied

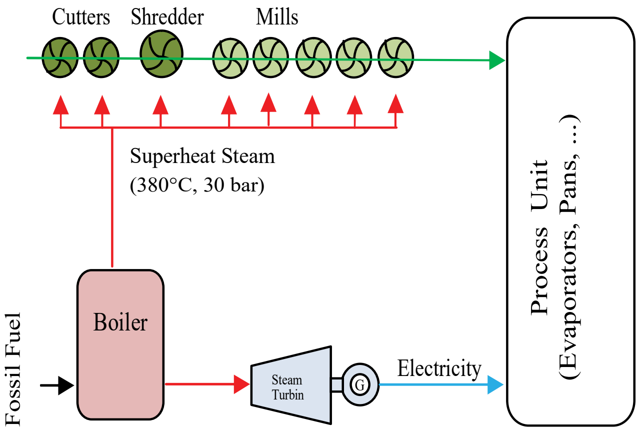


Fig. 1. Energy conversion in the studied sugarcane plant

plant, the main energy source is thermal. As it is shown in Figure 1, a boiler is responsible for generating superheat steam (30 bar, 380°C) which will be used in different destinations: turbine/generator unit, mill and preparation unit, reducer, and the boiler's internal usages.

Electricity demand of the whole plant is supplied by two 4.8 MW steam turbines. Nevertheless, during startup when we don't have any steam generation, the electricity is imported from the national grid. Another important superheat steam consumption takes place at the mill and preparation unit. The previously mentioned cutters, shredder and mills are all driven by steam turbines. The shaft power of cutters, shredder and mills' steam turbines are 1, 2.3 and 1.1 MW, respectively. A portion of steam generated by the boiler is used inside the boiler and water circuit. Each boiler has a forced draft fan (FD fan) which works by an electrical motor in start-up period and by a single stage steam turbine during normal operation. This also applies to boiler feed pumps, which operate with two steam turbine-driven pumps in normal operation and one electrical pump during startup. All of these four steam turbines (two for boiler feed pumps and two for two FD fans for two boilers) are fed by live steam generated by the boilers. Another small internal steam consumption that provides a source of preheating for the deaerator exists.

The exhaust steam of steam turbines of turbine/generator, mills and preparation units (saturated at P=2.05 bar) is sent to the process unit where their latent heat evaporates the water content of juice and syrup. Exhaust steam of turbines of FD fans and boiler feed pumps are saturated as well (at 4 bar). This 4 bar steam is mainly used for deaerator preheating, feed water preheating, and some heating loads inside the process unit (e.g. molasses heating). However, it should be stated that the main source of heat transfer in the process unit is the saturated steam with P=2.05 bar. At higher factory loads, the process needs more 2.05 bar steam than what exhausted by the steam turbines. In these situations, the reducer unit starts working to deliver the required extra steam. In the reducer, water will be sprayed into superheat steam to decrease its internal energy and convert it (30 bar, 380°C) to saturated steam at a pressure equal to 2.05 bar.

In general, the major energy consumption of the plant is fossil fuel, while required electricity is generated inside the factory (except start-up period). Live superheated steam generated by the fossil fuel is used in various plant components. In Figure 2, share of each section in using the superheated steam is illustrated at nominal condition at full load. The preparation & mill section consumes the majority of the steam and the process section uses no superheat steam as was mentioned above. However, the process section utilizes close to 60% of thermal energy delivered by boilers. Obviously, there are two reasons: (1) the exhaust steam from preparation & mill turbines, turbo-generators, steam turbines of FD fans and BF pumps, enters the process section, (2) heat transferat the process section is in two-phase and due to high latent heat of water, total amount of energy transfer is high.

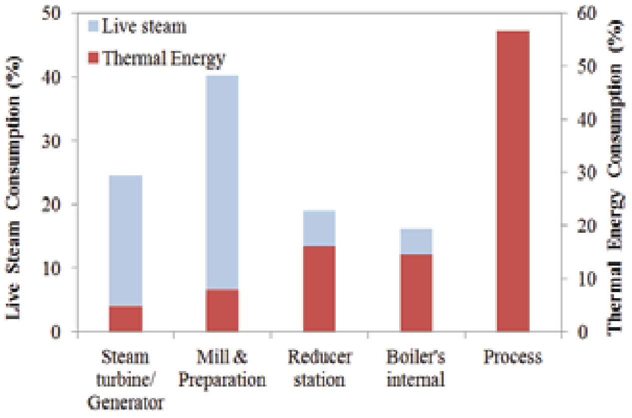


Fig. 2. Share of live steam and thermal energy consumption in the factory

Energy audit of this plant was performed in three main steps:

- Analyzing available data on fuel and electricity consumptions as well as raw sugar production
- Measuring the key parameters of the plant
- Analyzing the measurements to find out major sources of energy wasting

According to the ASHRAE levels of energy audit, the level of the presented work is level 2. Main sources of primary study were electricity and natural gas bills during the past four years. Daily statistics of sugar production and fuel consumption were analyzed to draw a picture about the energy usage in this plant over the past years. Afterward, we measured key parameters when the plant started to work in 2019-2020. Flow rate, temperature, electrical power of the main streams were measured by portable devices. Moreover, the flue gas of the boiler was analyzed for calculating the thermal efficiency. A thermography camera was used to compute energy loss from different surfaces. In some situations, data from the in-site measurement devices were utilized, for example for the syrup Brix.

To analyze the plant from an energy perspective, all the measured and gathered data were taken into account. The studied sugarcane plant has a capacity of 100,000 tons of raw sugar production per year while in the past years it had an average production of 75,000 tons/year. The plant consists of four main sections: boilers, turbo-generators, preparation and mill house, and process unit. Therefore, analysis was performed by calculating isentropic efficiencies of turbo-generators (2 sets), isentropic efficiency of preparation and mill turbines (8 turbines and gearboxes), efficiency of a water-tube boiler, energy loss due to poor insulation, and energy loss in process hall. According to ASME PTC 4, the indirect method for calculating boiler efficiency was used.

The following are some equations that are used in calculations:

Steam turbine isentropic efficiency:

$$\eta_{is} = 100\frac{h_{in}-h_{out}}{h_{in}-h_{out.is}} \qquad (1)$$

Steam turbine energy (or thermal) efficiency:

$$\eta_{t} = 3.6\times10^{5}\frac{P}{M_{S}(h_{in}-h_{out})} \qquad (2)$$

Steam leakage from holes:

$$\dot{V} = C\times A\times\sqrt{\frac{2\Delta P}{S\times\rho_{w.std}}} \qquad (3)$$

Heat loss from surfaces:

$$q = \left[\varepsilon.\sigma.\left(T_h^4-T_c^4\right)+\alpha.\left(T_h-T_c\right)\right]\times A_h \qquad (4)$$

Where h, $\dot{M}_s$, ΔP, S, $\rho_{w.std}$, $\dot{V}$, q, α, ε, A_h, and P are enthalpy (kj/kg), mass flow rate to steam turbine (kg/h), pressure difference between steam pressure inside and outside of a hole (pa), specific gravity of the steam, specific density of steam at standard conditions (kg/m^3), steam leakage flow (m^3/s), heat transfer rate (w), Stephan Boltzmann constant (w/m^2.K) , emissivity coefficient, hot surface area (m^2), and power production of steam turbine (kW), respectively. Indices of "in" and "out" denotes to inlet and outlet of the steam turbine while "h" and "c" refers to hot and cold (ambient air) objects.

Results and discussion

Using electricity and natural gas bills of the last four years, the plant's overall energy consumption was calculated in Gigajoules. In Figure 3, the specific energy consumption is illustrated from the working season of 2015-2016 to 2018-2019. The energy used to extract sugar from sugarcane decreased in the time period of 2015-2018. The sharp rise of specific energy consumption in 2018-2019 was mainly due to extensive damages on sugarcane crop caused by flood. It is worth mentioning that the plant generates the required electricity during sugar production while it needs the electricity from the national grid only when the process section is not working (often from April to September). When raw sugar was being produced, imported electricity made up 1.25% of all energy used.

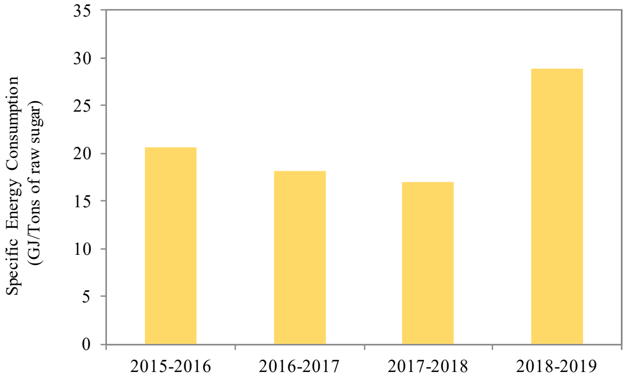


Fig. 3. Annual average of specific energy consumption during past 4 years

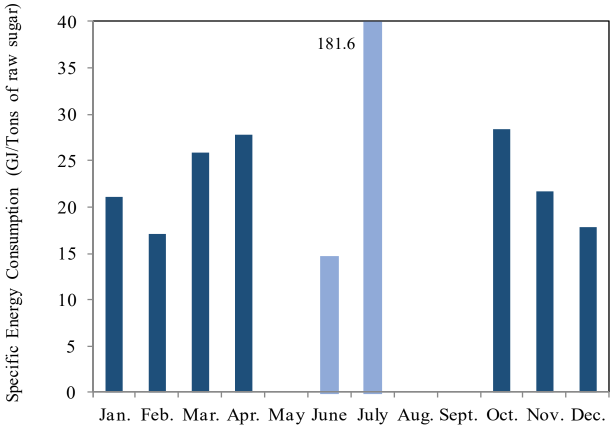


Fig. 4. The specific energy consumption during one year (averaged for 4 years)

The average monthly distribution of specific energy consumption is shown in Figure 4. The average is for the last 4 years. It is obvious that specific energy consumption was minimum in February. While we had the highest energy consumption in March. June and July's values (14.7 and 181.6) only apply to a single year and are not to be regarded as the maximum and minimum months. It was due to the consequences of the destructive flood. The variations of specific energy consumption could be a function of inlet sugarcane (amount and stop intervals) that depends on the agricultural section. From the beginning of sugar extraction in October, the plant was not in its full load because of lack of sugarcane supply. So, we had a boiler working at a load of 60-100% while there were even periods with no sugarcane supply. The energy consumption decreased gradually and in February the plant worked at its highest load. The remaining crop entered the plant oscillating. Therefore, the specific energy consumption increased.

Plotting the electrical energy consumption of the studied plant during the past four years showed that the specific electrical energy consumption is in relation with raw sugar production exponentially (Figure 5). This trend is rational because there are some nearly constant electrical loads which will increase the amount of kW/ton in lower sugar production rates.

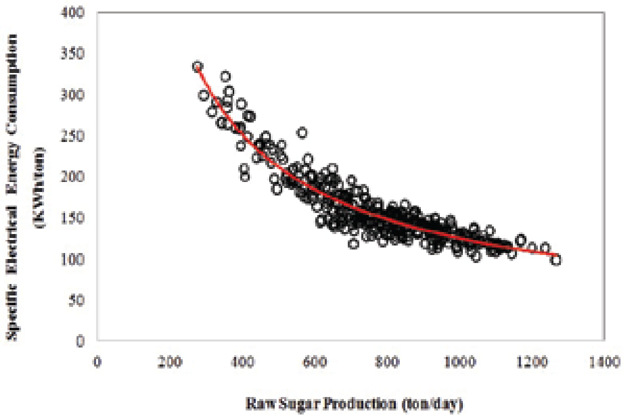


Fig. 5. Relationship between daily raw sugar production and specific electricity consumption

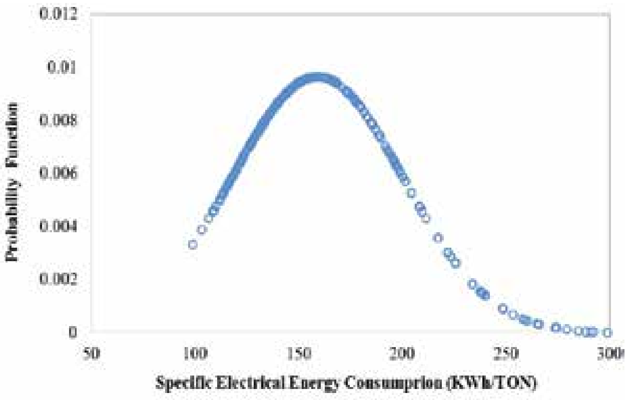


Fig. 6. Probability function of specific electrical energy consumption

In Figure 6, the probability function of the electrical energy consumption of the plant is shown. In 95% of the operation times, the plant was working in the range of 120-200 kWh/ton. This scattered normal distribution is relatively wide with a standard deviation of 41.3 kWh/ton. This is evidence of improper planning of the plant and lack of coordination between the harvesting section and the processing plant. There is a considerable potential for improvement by narrowing the curve of Figure 6. This could be done by a better planning and scheduling of the production.

Boiler efficiency was calculated by loss-method at various loads. The efficiency reduction from the nominal value (90.5%) is shown in Figure 7. Efficiency drop wasapproximately in the range of 0.5-2.5%. At lower loads, the boiler efficiency dropped more, because of the higher excess air. This is mainly due to dry gas loss. The dry gas loss rose from 6.7% to 8.4% when the boiler load decreased from 80% to 40%. Minimizing the sum of dry gas and unburnt

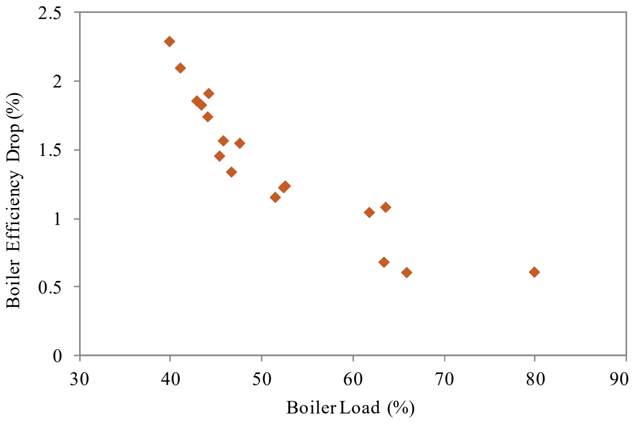


Fig. 7. Efficiency reduction of boiler in different loads

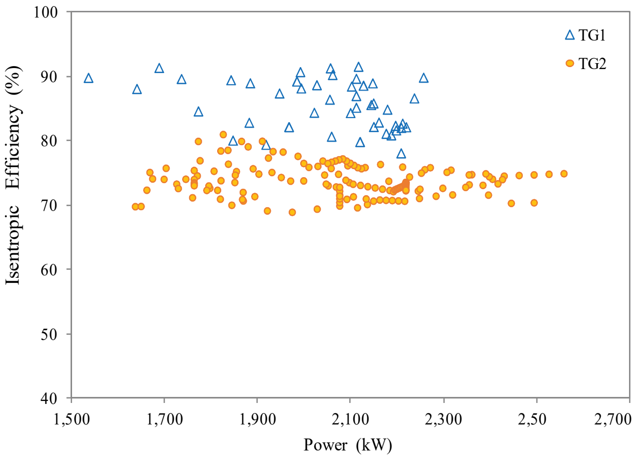


Fig. 8. Isentropic efficiency of steam turbines coupled with electricity generator

carbon losses, requires an excess air to be in an acceptable range close to the optimum excess air. This optimum value depends on the load, boiler design and fuel type. For example, for a coal fired boiler it might be 20±10% (Zhang, 2015) while for a natural gas fired one could be close to 10±5% (Abroshan, 2020).

To find out the impact of operation on this reduction, boiler efficiency reduction was divided into two categories: due to poor operation, and due to degradation of boiler. The results showed that there is a nearly constant 0.6% efficiency drop for all loads because of boiler degradation (0.4-0.8%). But very high or very low combustion air set points were responsible for 0.4-1.7% efficiency reduction. The share of misoperation in boiler efficiency drop is considerably higher especially at lower loads where excess air was dramatically larger (more than 100%). At higher loads, however,boiler operators used an excessive low excess air setpointresulted in more unburned carbon loss and low boiler efficiency.

To check the root cause of efficiency drop due to degradation, stack temperature was analyzed. Stack temperature at different loads was 10-30°C higher than what it should be based on design specifications. If this boiler was in its good conditions (i.e. without degradation), it did not need any de-superheating spray at loads between 40% and 80%. But, in measured conditions we had a 5-12 t/h de-superheating spray. These two deviations from design condition could be interpreted as an internal fouling in boiler's waterwall tubes. The water side fouling in waterwall leads to a reduction of heat transfer from flame to water/steam mixture. Therefore, assuming a constant air and fuel flow, flue gas exits the furnace with higher temperature. This could have two consequences: higher stack temperature, and higher heat transfer to superheaters which follows to more de-superheating water.

Two steam turbines each generating 4.9 MW are at service to supply the electrical energy requirement of the plant. The isentropic efficiency of them was calculated from measured values at different loads. During 4 hours, when loads of steam turbines were in range of 1.5-2.6 MW, the isentropic efficiency of the steam turbines were plotted in Figure 8. It could be seen that turbine number 1 is working with a significant lower internal losses. Unit 1 has an average isentropic efficiency of 86% while the average isentropic efficiency of unit 2 is 73.7%. There is a great difference and also a huge improvement opportunity. In Figure 9, the energy efficiency of these two steam turbines are shown during more than 5 operating hours. This parameter, which primarily displays the performance of gearboxes, shows that the unit 1 gearbox is in poor condition. Consequently, even though unit 2's steam turbine performs poorly, it has a much better gearbox than unit 1.

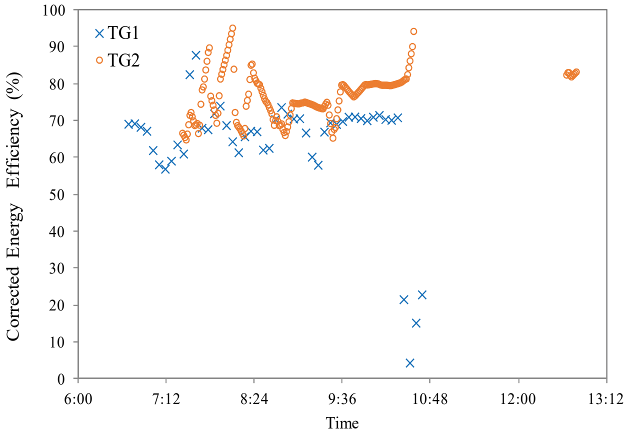


Fig. 9. Energy efficiency of steam turbines coupled with electricity generator

In the area where sugarcane is prepared, there are seven more steam turbines. These turbines are coupled with some rotaries in series (two cutters, one shredder, and five mills) which convert sugarcane into syrup. The steam turbines are coupled with gearboxes. During the onsite measurement, one of the cutters was out of service. The average isentropic efficiencies of these 6 turbines were calculated and the results are shown in Figure 10. The shredder turbine is significantly degraded, as evidenced by its low isentropic efficiency shows. Turbine of cutter #2 performance better, despite the fact that it is a single stage turbine. Thermal efficiencies of these steam turbines, that mainly reflect the performance of gearboxes, arehigher for mill turbines, averaging 93.4%. Gearboxes of

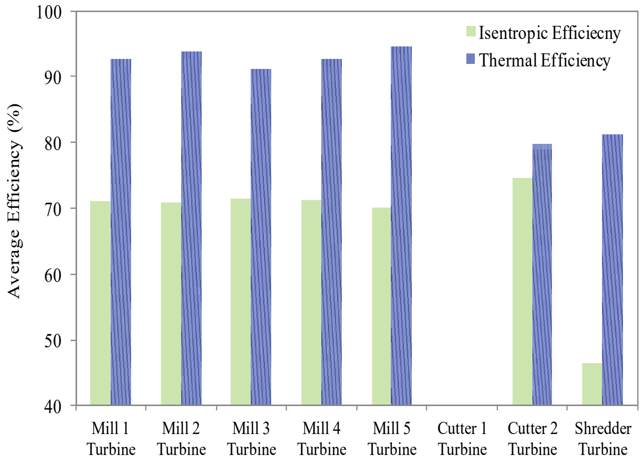
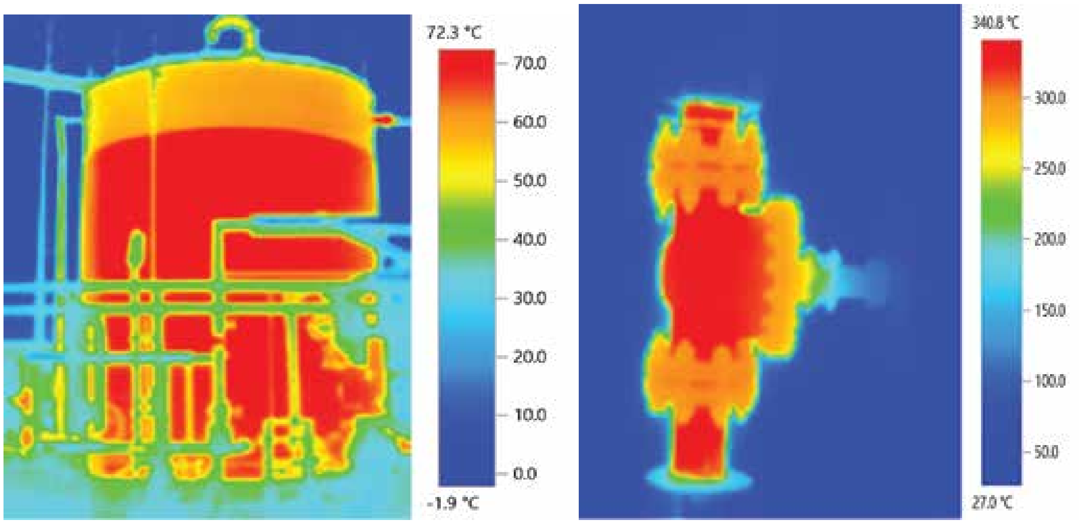


Fig. 10. Isentropic and thermal efficiency of steam turbines in preparation and mill house

cutter #2 and shredder are more worn with a thermal efficiency of 79.7% and 80.8%, respectively.

To estimate the amount of heat loss due to improper or insufficient insulation, more than 80 thermal images were taken by a thermographic camera. In Figure 11, two samples of these images are illustrated. The hotwell tank's inadequate insulation, as shown in the Figure 11 (a), allowed a thermo vision camera to detect the water level. Through this survey it was revealed that insulation of piping system is completely efficient while there are some drawbacks in insulation of junctions, valves, and tanks. The summary outcomes of heat loss for 61 pieces of equipment is presented in Table I. These values are calculated for ambient temperature of 18°C and the wind speed of 6 m/s for outdoor components and zero for indoor. Thermal loss from the boiler's surface is minimized because ofits properly maintained insulation. The main issue in insulation belongs to water storage tanks (4 tanks) whichlose close to 4 MW of heat.

Managing the electrical loads of the factory is another promising technique to decrease the annual energy consumption (Figure 12). The plant's location in an extremely hot area means that summertime space cooling



(a) (b)

Fig. 11. Thermographic images of (a) hotwell tank and (b) valve of inlet steam to mill turbine #1

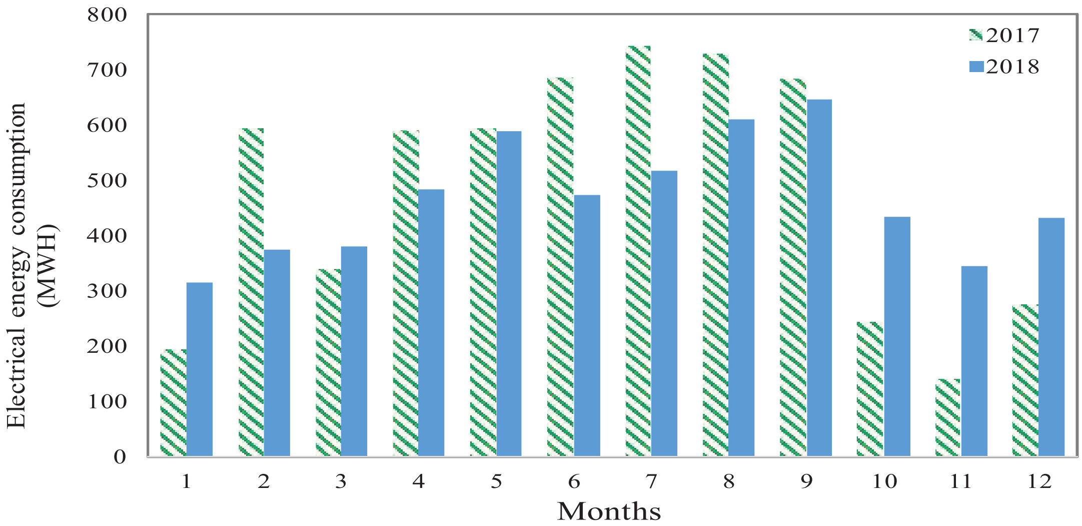


Fig. 12. Total external electricity consumption over months for two years

Table I. Radiation loss of four categories

Item No.	Equipment	Total loss (kW)
1	Boiler surface	1164
2	Water storage tanks	3865
3	Valves and pipe junctions	158
4	Steam traps	28

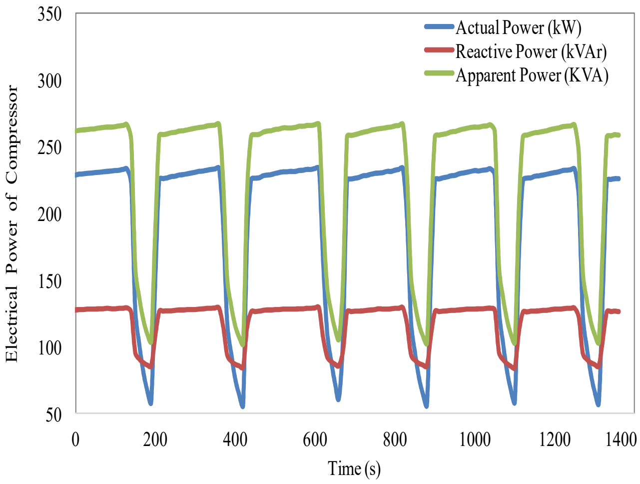


Fig. 13. Cyclic operation of compressors used for instrumentation air

loads will increase significantly. Other electrical consumptions in non-operating periods (e.g. summer) consist of lighting, periodic repairs, and office equipment. All of these loads and especially the cooling load could be decreased considerably by a demand response and shifting the working hours (peak shedding). During the summer of 2018, when the site temperature exceeded 50°C, this was done. By doing this in August, the electrical consumption decreased by 200 MWh compared to the past years, even thoughthe temperature was higher in 2018.

The power consumption of the instrument air compressors were measured during the test period for 23 minutes using clamp power meter. From four compressors, the forth one was working as the master compressor. Its electrical power consumption is shown in Figure 13. The master compressor worked in a load-unload control scheme. Over time, the pattern shown in Figure 13 reappears. After 170 seconds of loading the compressor goes to unloading conditions for 70 seconds. In the loading and unloading sessions, the power consumptions are 250 and 60 kW, respectively. Thus, there is an improvement opportunity by changing the control scheme to a drive control. In this case, instead of switching between 60 and 250 kW periodically, the compressor will work continuously on 175 kW which results in 43 MWh energy saving, annually.

To compare conditions of the tested plant with the nominal one, steam and thermal energy consumption of each section is presented in Figure 14 (in comparison with Figure 2). Due to lower load of the plant, the reducer station utilized less steam. The turbo-generator consumed approximately the same amount of live steam The main reasonis that electrical loads are almost constant by changing the load of the plant. As a result, its share of live steam consumption increases as plant load rises. In comparison to full load at nominal condition, the process section's portion of thermal energy consumption increases slightly.

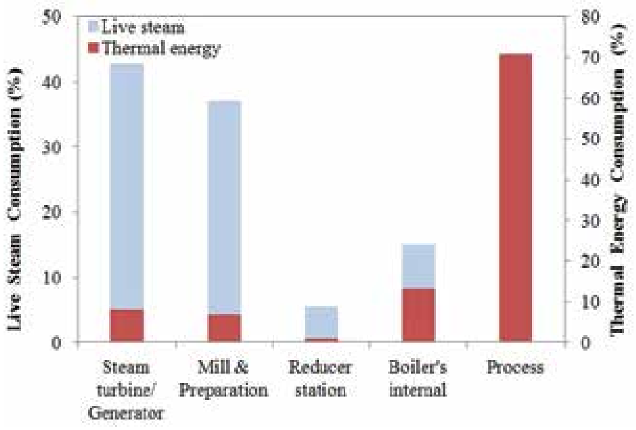


Fig. 14. Share of each section in consumption of thermal energy and steam outlet from the boiler

Conclusion

Performance of different components in a sugar factory was measured and presented. Some of these parameters were presented over the course of a year, while others were presented over the course of a day or even an hour. The boiler, steam turbines (for electricity generation and prime moving), instrumentation compressors, and electrical equipment were all analyzed. In addition to calculating the energy efficiency of various pieces of equipment, topics such as load management and thermal insulation were taken into account.

According to the findings, the boiler's energy efficiency has been reduced by 0.5% to 2.5%. This range of efficiency drop depends on the boiler load (40% to 80%), with the efficiency drop being highest at the lowest boiler load. Close to

0.4-0.8% of this reduction is caused by boiler aging. However, the boiler's poor operation setting for combustion excess air is the main reason of the severe reduction in efficiency. Inappropriate combustion air setting was responsible for 0.4-1.7% of the efficiency drop. There was also a huge amount of carbon monoxide emission at higher loads due to this improper air ratio that caused by fault of boiler's operators and resulted in a significant boiler efficiency drop.

Steam turbines used to generate electricity were also evaluated. Turbine of unit 1 had a better internal steam path condition, but its gearbox (and mechanical losses) were not functioning as efficiently as unit 2's. There are eightadditional steam turbines in operation; one of them was not in service. Among these turbines that act as prime movers of cutters, shredder, and mills; the ones for shredder had a poor internal condition based on their low isentropic efficiency compared with design values. The gearboxes for the cutter and shredder had also deviated significantly from their designed values.

Thermal imaging of the equipment revealed significant energy loss, particularly from the surface of the water storage tanks, which was close to 4 MW. The factory has a significant opportunity to reduce energy waste by using proper insulation. Another option for reduction of energy consumption is peak shedding that is a good opportunity in hot summers. In addition, while current instrument compressor is working with a load-unload control system, measurements and calculations showed that working with a drive control will decrease the electrical energy consumption by near 43 MWh/year. It can be seen that the process is using more energy by comparing the distribution of thermal energy usage among various factory sections to the design share. It is proof of numerous equipment malfunctions and leaks in the processing plant.

Even though these measurements and calculations are made for a particular sugar factory, they can draw attention to areas that might be significant in other sugar factories. Performing semi-overhauls, repairs, good insulations, and a few replacements can lead to higher energy efficiency. But the proper operation should not be overlooked or underestimated.

References

Abroshan H (2020), An integrated model to study the effects of operational parameters on the performance and pollutant emissions in a utility boiler, *Journal of Thermal Engineering* **6**(4): 474-498. https://doi.org/10.18186/thermal.764157

Bayrak M, Midilli A and Nurveren K (2003), Energy and exergy analyses of sugar production stages, *International Journal of Energy Research* **27**(11): 989-1001. https://doi.org/10.1002/er.916

Boharb A, Allouhi A, Saidur R, Kousksou T and Jamil A (2017), Energy conservation potential of an energy audit within the pulp and paper industry in Morocco, *Journal of Cleaner Production* **149:** 569-581. https://doi.org/10.1016/j.jclepro.2017.02.090

Çay A (2018), Energy consumption and energy saving potential in clothing industry, *Energy* **159:** 74-85. https://doi.org/10.1016/j.energy.2018.06.128

Chantasiriwan S (2019), Distribution of heating surface areas in sugar juice evaporation process for maximum energy efficiency, *Journal of Food Process Engineering* **42**(3): e12998. https://doi.org/10.1111/jfpe.12998

Cortez LAB, Baldassin R and de Almeida E (2020), Energy from sugarcane *In:* Sugarcane Biorefinery, Technology and Perspectives, *Academic Press,* pp 117-139. https://doi.org/10.1016/b978-0-12-814236-3.00007-x

Dhakar MK, Choudhary P and Singh NK (2021), Performance improvement of a sugar mill through EXERGY analysis, Materials Today: Proceedings. https://doi.org/10.1016/j.matpr.2021.02.427

Engin T and Ari V (2005), Energy auditing and recovery for dry type cement rotary kiln systems—A case study, *Energy conversion and management* **46**(4): 551-562. https://doi.org/10.1016/s0140-6701(05)82284-2

Erdal G, Esengün K, Erdal H and Gündüz O (2007). Energy use and economical analysis of sugar beet production in Tokat province of Turkey, *Energy* **32**(1): 35-41. https://doi.org/10.1016/j.energy.2006.01.007

Gunness D, Chang KKW and Lau AF (2007), Cleaner production assessment in a sugar factory, In Proc. Int. Soc. Sugar Cane Technol. **26:** 1397-1403.

Hofsetz K and Silva MA (2012), Brazilian sugarcane bagasse: Energy and non-energy consumption. *Biomass and Bioenergy* **46:** 564-573. https://doi.org/10.1016/j.biombioe.2012.06.038

Kluczek A and Olszewski P (2017), Energy audits in industrial processes, *Journal of cleaner production* **142:** 3437-3453. https://doi.org/ 10.1016/ j.jclepro.2016.10.123

Klugman S, Karlsson M and Moshfegh B (2007), A Scandinavian chemical wood pulp mill. Part 1. Energy audit aiming at efficiency measures, *Applied Energy* **84**(3): 326-339. https://doi.org/10.1016/j.apenergy.2006.07.003

Lambert C, Laulan B, Decloux M, Romdhana H and Courtois F (2018), Simulation of a sugar beet factory using a chemical engineering software (ProSimPlus®) to perform Pinch and exergy analysis, *Journal of Food Engineering* **225:** 1-11. https://doi.org/10.1016/j.jfoodeng.2018.01.004

Manochio C, Andrade BR, Rodriguez RP and Moraes BS (2017), Ethanol from biomass: A comparative overview, *Renewable and Sustainable Energy Reviews* **80:** 743-755. https://doi.org/10.1016/j.rser.2017.05.063

Mendoza TC and Samson R (2002), Energy costs of sugar production in the Philippine context, *Philippine Journal of Crop Science* **27**(2): 17-26.

Rao GRN and Naqaraian M (2012), Energy Efficiency in Indian Sugar Industries.

Renewable Fuels Association (RFA) (2015), Ethanol industry statistics, Washington, DC, USA, www.ethanolrfa.org

Şahin HM, Acir A, Altunok T, Baysal E and Koçyiğit E (2010), Analysis of exergy and energy of sugar production process in sugar plant, *Journal of the Energy Institute* **83**(3): 178-185. https://doi.org/ 10.1179/014426010x12759937396911

Soppimath VM and Hudedmani MG (2017), Energy Audit and Energy Management in the Sugar Industry. MATTER: *International Journal of Science and Technology* **3**(1): 10-26. https://doi.org/10.20319/ mijst.2017.31.1026

Taner T and Sivrioglu M (2015), Energy–exergy analysis and optimisation of a model sugar factory in Turkey, *Energy* **93:** 641-654. https://doi.org/10.1016/j.energy.2015.09.007

Taner T and Sivrioglu M (2017), A techno-economic & cost analysis of a turbine power plant: A case study for sugar plant, *Renewable and Sustainable Energy Reviews* **78:** 722-730. https://doi.org/10.1016/j.rser.2017.04.104

Zhang G (2015), Study on optimum excess air coefficient for power plant boilers. In International Conference on Mechatronics, Electronic, Industrial and Control Engineering (MEIC-15), Atlantis Press, pp 1374-1378. https://doi.org/10.2991/meic-15.2015.315