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ORIGINAL ARTICLE

Energy performance comparisons and enhancements in the sugar cane industry

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Abstract

In this study, energy-related operational parameters for modern and traditional (conventional) sugar mills are analyzed, with the goals of identifying improvements in energy efficiency and potential for surplus electricity export. Results show that the power-to-heat ratio of modern and traditional mills is clearly distinct, lying in the ranges of 0.3–0.5 and 0.04–0.07, respectively. Modifications under consideration for the traditional mills include the following upgrades: electric drives and higher capacity back-pressure turbine (case 1); high-pressure boiler, condensing extraction steam turbine and electric drives (case 2); and improvements in case 2 plus bagasse drying (case 3). The thermodynamic impact of these modifications shows that more power is generated as the modification becomes more advanced. Case 1 exhibits a modest increase in cogeneration efficiency (4%) as compared to the base case, while the cogeneration efficiency increase is more marked for cases 2 and 3 (21% and 31%, respectively). Surplus power was studied in a regional context, where it was found that the contribution of 19 retrofitted sugar mills in nine Brazilian regions could supply 30% or more power as compared to current installed power capacity. The economic analysis showed that levelized cost of electricity (LCOE) was lowest for case 1 (11 USD/MWh) and highest for cases 2 and 3 (58 USD/kWh).

Keywords Sugarcane · Traditional mills · Modern mills · LCOE · Energy performance · Model

NomenclatureCharacterparameter/unit

F	moisture content (%)
$\dot{P}$	power (kW) or (MW)
Δh	enthalpy difference (kJ/kg)
LHV	lower heating value (kJ/kg) or (MJ/kg)
$\dot{m}$	mass flow (kg/s)
$\dot{Q}$	heat flow (kW) or (MW)

Symbolparameter/unit

γ	electric motor related loss (%)
η	efficiency (%)
α	power-to-heat ratio

Subscript

d	dry basis
co	cogeneration
net	net value
new	new value calculated using new moisture content
ex	excess
BC	base case
tr	transmission
Drive	related to electric motor drive
el	electrical
tot	total
B	boiler
f	fuel
me	mechanical
st	steam
ps	process

Abbreviations

CEST	condensing extraction steam turbine
TC	tonne of cane
TCH	tonne of cane per hour
BPT	back-pressure turbine
PBP	payback period

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EES	Engineering Equation Solver
VFD	variable frequency drive
LCOE	levelized cost of electricity
CRF	capital recovery factor
HP	high pressure

1 Introduction

Sugarcane and sugar beets are important cash crops, ranking in the top ten in value internationally [1]. Around 70% of the global sugar supply, currently exceeding 120 million tonnes per year, is derived from sugarcane, whereas the remaining 30% is obtained from sugar beets [2]. Sugarcane is grown in more than 100 countries worldwide [3]. According to FAOSTAT [4], Brazil ranks first in sugarcane production globally, accounting for about 25% of global sugar production and 50% of sugar exports [3, 5]. With the exception of corn/maize, sugarcane is one of the few crops that can be readily integrated with cogeneration at large scale. According to a review report conducted on the cogeneration potential of various sugar mills in different countries [6], several sugar mills are involved in surplus power production as a means to obtain revenues from electricity sales and consequently contribute to the energy mix of the country. This is due to the fact that energy demand is increasing worldwide especially in developing countries; therefore, looking into the energy potential of sugar mills has been one alternative to address the shortage of energy supplies.

Energy efficiency improvement measures in sugar mills have been and continue to remain critical for both cogeneration and in the sugar/ethanol processing units. In practice, most attention has been paid to cogeneration, although several studies have clearly illustrated the benefits of measures on the process side. Some of the possible improvements include the following [6–9]: steam consumption reduction in the crystallizers, installation of continuous vacuum pans, installation of cane diffusers in place of mill rollers, increase in number of effects of multiple evaporators, and use of maximum vapor bleeding in multiple effect evaporators. Regarding energy efficiency measures in cogeneration units, several case studies are available with the aim of increasing the net electricity production capacity. The most common modifications in the cogeneration units include installation of high-efficiency boilers, replacement of steam-driven mechanical drives with electric drives, upgraded steam turbines, and bagasse drying [6–10]. In particular, variable speed electric drives have been proven to be a better option for replacing the steam turbines used for mechanical power generation in traditional sugarcane mills [7, 11]. Among others, the advantage of having electric drives instead of steam turbines is to efficiently utilize the high-pressure steam and be able to create operation flexibility of generating surplus electrical power [10–12]. In addition, variable speed electric drives work to match the varying load of cane crushed. Beyond this advanced cogeneration technologies such as biomass integrated gasification combined cycles (BIG-CC), biomass integrated gasification with gas turbine (BIG-GT) and biomass integrated gasification with steam-injected gas turbine (BIG-STIG) are in the development stage, with further implementation dependent upon commercial-scale demonstration of bagasse gasification [8]. One of the most common modifications in the cogeneration units of sugar mills is the installation of high-pressure and high-temperature boilers. The goal with the introduction of such boilers is achieving higher live steam parameters (temperatures above 450 °C and pressures above 45 bar [8]) which can then be utilized in the power steam turbines to obtain surplus power. On the other hand, the moisture content of bagasse affects the performance of the boiler in such a way that the drier the bagasse, the better its heating value which in turn will lead to improved combustion temperature. This means the boiler efficiency may be further improved with a drier fuel.

In examining sugar mill cogeneration more closely, a distinction can be made between so-called conventional, or traditional mills, and modern mills. Conventional (traditional) sugar mills are characterized by the following traits: low-pressure and low-temperature boilers (20–30 bar and 300–400 °C, respectively); back-pressure turbines (BPT) for providing steam to various mechanical equipment (rollers, shredders, and pumps); little or no surplus electrical power production; and occasionally parallel ethanol production. Traditional sugar mills lacking electrical power export generally supply 10–20 kWh electrical or mechanical energy/t cane (TC) and have an internal heat demand of 480–550 kg steam/TC [13]. In traditional sugar mills, the most predominant type in terms of total tonnage, use of back-pressure steam turbines along with burning bagasse (having 50% moisture content) in low steam parameter boilers leads to an underutilization of energy conversion from the cane feedstock. Such a practice for cogeneration in sugar mills has been in place for decades, although nowadays, the interest is to install high-efficiency cogeneration systems for enabling export of surplus power to the grid. A typical traditional sugar mill can produce 250–280 kg bagasse per tonne, which equates to a heat demand of roughly 2 kg steam/kg bagasse [6]. However, in such mills where back-pressure turbines use the sugar/ethanol process as their condensing unit, having excess bagasse at the end of the season is not practical as during off-season there is no possibility to utilize the bagasse for energy purposes if it is not sold to other stakeholders as a fuel, for example, in pellet form [14]. This makes the cogeneration system in traditional mills inflexible as they are forced to utilize almost all produced bagasse during the milling season. In addition, many traditional sugarcane mills are built as stand-alone units where there is no national grid connection, thus limiting the sugarcane industry in generating surplus power even if the potential for this is present. In-field burning of cane trash (tops and leaves), a practice common in areas lacking mechanized harvesting, represents a loss of up to 1/3 the theoretical amount of energy available in the sugarcane plant [15, 16].

Modern sugar mills are characterized by high-pressure (45–80 bar) and high-temperature boiler installations (above 450 °C) [8]. The cogeneration unit of such mills is usually equipped with condensing extraction steam turbine (CEST) technology, and thus, the production of surplus electrical power is common. Electrical drives are used in most modern sugar mills in lieu of steam turbines for producing mechanical power, which improves overall energy efficiency. Other equipment such as diffusers in the cane juice extraction process are hallmarks of modern sugar mills.

Energy performance comparisons between traditional and modern sugar mills have been conducted largely on a case-by-case basis. A retrofit analysis of a sugar mill in *Indonesia* shows that the upgraded CEST cogeneration system (same steam parameters as the base case plant, 30 bar/340 °C, but with electric drives) can export 45 kWh/TC of surplus electrical energy to the grid [8]. A retrofit utilizing higher steam data (80 bar, 480 °C) and electric drives lead to a 50% gain in exported electricity. Another study reports that a sugar mill located in *Brazil* having a cogeneration system with back-pressure steam turbine (BPST) and low steam parameters (22 bar and 300 °C) generates up to 10 kWh/TC surplus electricity [14]; while a second study for a Brazilian sugar mill employs BPST and high steam parameters (67 bar and 480 °C) generates 60 kWh/TC surplus electricity. This source also reports on a sugar mill located in *India* having a CEST technology and high steam parameters (67 bar and 495 °C) that generate surplus electricity in the range 90–120 kWh/TC, whereas other sugar mills in *India* with CEST technology and higher steam parameters (87 bar and 515 °C) generate a surplus electricity of 130–140 kWh/TC.

The CEST cogeneration system of sugar mills involves usage of all the available bagasse during the crushing season, and it allows production of surplus power even during the off-season by operating the turbine in condensing mode. As described in the previous paragraphs, there are well-known modification technologies that improve the overall energy efficiency of the cogeneration units of sugar mills. On the other hand, there is little information in the literature regarding whether the theoretically claimed energy efficiency gains due to the modifications are practically achieved in sugar mills, and if modern sugar mills really are energy efficient. Hence, an analysis of the theoretical operation parameters of sugar mills needs to be compared with practical operation parameters with the purpose of identifying if the theoretical amount of energy efficiency gains is actually achieved. Since the economy is the driving force for efficiency improvements, it is as well important to include economic parameters in such an analysis. Thus, in this study, typical theoretical operation parameters for efficiency improvements towards actual operation parameters are analyzed as well as the capital cost for efficiency improvements. In addition, aside from the previously mentioned general statistics on modern and traditional sugar mills, there is a lack of compiled database of the operational parameters of sugar-producing countries. Hence, in this paper, operational parameters of a range of sugarcane mills are gathered and analyzed with the purpose of comparing selected key parameters. The interrelation of such parameters and their influence on the characteristic differences of traditional versus modern mills are then used to draw conclusions.

1.1 Methodology

The methodology followed in this work is outlined as follows:

- Operational parameters of cogeneration performance from both traditional and modern sugar mills are gathered from the literature and via direct correspondence with relevant persons at some of the sugar mills.
- Cogeneration performance parameters for both the traditional and modern sugar mills are analyzed.
- Modification of the traditional sugar mills is made and compared with the performance of the modern mills.
- A simplified economic analysis of the modification of the traditional sugar mills is made.
- A sensitivity analysis is made using two approaches.

The above mentioned analyses are carried out through models built using Engineering Equation Solver (EES).

1.1.1 Input data used for the cogeneration-based analysis

A database of 2800 sugar mills (2330 sugarcane based and the remainder based on sugar beet) was acquired through email communication with F.O. Licht team [17]. Table 1 summarizes the key parameters (state of operation and capacities), number of mills, and countries represented. The number of entries is quite extensive; however, only about 5% of the raw data is presented in a form that can be analyzed, i.e., listing of crushing capacity, electric power capacity, and sugar/ethanol production. In examining the overall performance of modern versus traditional sugar mills, one might expect to see a clear demarcation in terms of electric power capacity as a function of crushing capacity. This relationship is plotted in Fig. 1, which shows the set of data points listed in the last row of Table 1, grouped according to country of location. (Country-based data for locations with less than three mills reported are grouped together.) A linear regression analysis on data obtained for Australia, Brazil, Guatemala, India, and Mexico reveals a weak or non-existent correlation in aggregate or at the country level. Moreover, Fig. 1 shows that it is not possible to identify a distinct value in cane crushing

Table 1 Number of sugarcane mills and countries represented

Parameter	Number of mills	Number of countries represented
Total number of raw data points (operational, projects, under construction)	2330	99
Operational	1953	94
Operational with cane crushing data	221	42
As above and with electric power capacity data	169	23
As above and with ethanol/sugar production data	107	18

capacity that would stepwise divide modern versus traditional mills. These findings point to the need to look beyond macro-scale data of the type available from Licht [17] in order to conduct a more thorough analysis.

Using the Licht data as a basis, the information gap was filled via a literature search and contact with mill owners and operators. Finding a sufficiently complete set of detailed mill data proved difficult, and in the end, a total of ten mills could be identified [18–30]. These mills are located in Africa (Ethiopia, Mauritius), Asia (India, Sri Lanka), Australia, and South America (Brazil), thus providing good geographic spread. The inclusion of mills in Brazil, India, and Australia means that the three of the top ten sugar-producing nations are represented. A compilation of the selected mills along with the detailed mill data is listed in Table 2. Even though the number of mills is reduced to a small subset of the Licht database, the level of detail combined with the operational characteristics is judged to represent a reasonable cross-section of modern and traditional mills.

1.1.2 Heat balance equations

The equations used for the calculation are presented below.

The LHV of bagasse on dry basis where it is not specified is taken as 17.6 MJ/kg based on calculations by Birru et al. [12], and the LHV on total basis is calculated from Eq. 1 [32].

$$LHV_t = LHV_d\cdot\left(1-\frac{F}{100}\right)-2443\cdot\frac{F}{100} \qquad (1)$$

where LHV_t is the lower heating value on total basis in kJ/kg,

LHV_d is the lower heating value on dry basis in kJ/kg

F is the moisture content of bagasse in %

Power output (mechanical and electrical) is calculated from Eq. 2.

$$\dot{P} = \dot{m}\cdot\Delta h \qquad (2)$$

where $\dot{P}$ is the power output in kW

$\dot{m}$ is the mass flow rate in kg/s

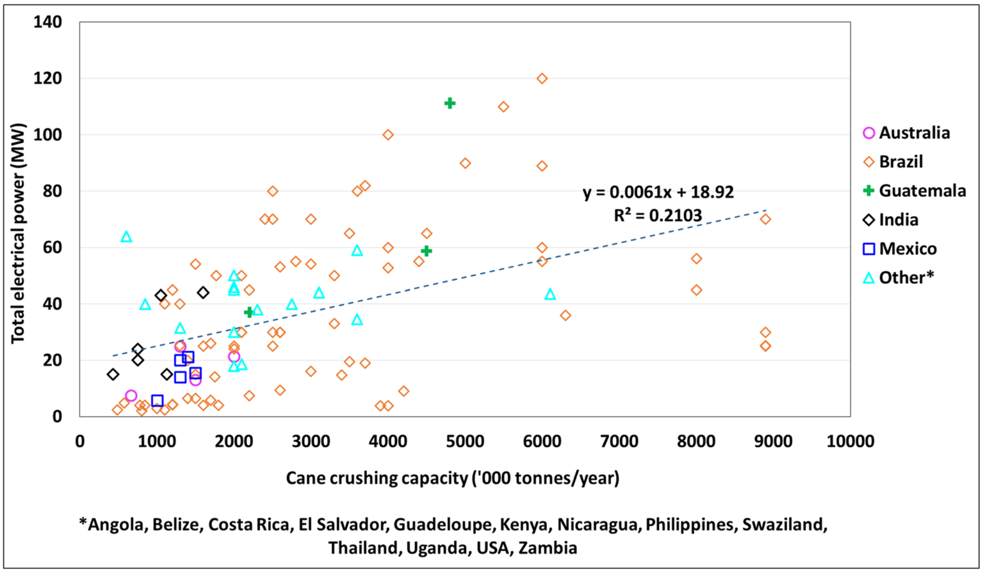
Δh is the change in enthalpy in kJ/kg

Heat flows (to the boiler and sugar/ethanol process) are calculated from Eq. 3.

$$\dot{Q} = \dot{m_{st}}\cdot\Delta h \qquad (3)$$

where $\dot{Q}$ is the heat flow rate in kW

$\dot{m}_{st}$ is the mass flow rate in kg/s



*Angola, Belize, Costa Rica, El Salvador, Guadeloupe, Kenya, Nicaragua, Philippines, Swaziland, Thailand, Uganda, USA, Zambia

Fig. 1 Total electrical power versus cane crushing capacity for mills that have electrical power generation and sugar/ethanol production values listed

Table 2 Summary of key cogeneration parameters for the selected mills

Parameters	Modern mills				Traditional mills					
	A[18, 19]	B[21]	C[22]	D[23, 24]	E[25]	F [26]	G[27]	H[28]	I[29]	J[30]
Name of sugar mill	Pioneer	Mackay[b]	Savannah[a]	Ugar	NR[d]	NR[d]	NR[d]	FSF	Pelwatte	Agroval
Location	Australia	Australia	Mauritius	India	Brazil	Brazil	Brazil	Ethiopia	Sri Lanka	Brazil
Cane crushed (tonne/h)	565	500	425	417	875	500	500	178	150	125
Sugar production (10^3 t/year)	265.2[20]	264[c]	286[17]	184[17]	230	238[c]	220[c]	100	50	264[c]
Total bagasse (tonne/h)	176	132	57	136	241	137		55	41	43
Net bagasse (tonne/h)	176[e]	132	57	128	198	126	135	54	41	33
Excess bagasse (tonne/h)	0	0	0	8	43	12		1	0	10
Total steam flow (tonne/h)	352	330	130	270	396	254	270	103	82	67
Mech power (kWh/TC)					23	9	16	18	14	13.7
Steam to process (tonne/h)	223	225	99	240	396	246	270	103	82	67
Total el power (MW)	61	43.3	28	44	9	7	6	5	2.2	2
El power for factory (MW)	17	9	9	14	9	7	6	5	2.2	2
Surplus power (MW)	44	34.3	19	30	0	0	0	0	0	0
Live steam T (°C)	383/483	260/510	525	480	300	320	320[f]	400	380	290
Live steam P (Bar)	31/66	18/64	82	62	22	22	22[f]	30	29	22
Steam to bagasse ratio		2	2	2	2	2	2	2	1.75	2
El power consumed (kWh/TC)	30	18	22	34		13	12	27	15	15
El power generated (kWh/TC)	108	86.6	66	106	10	13	12	27	15	15
Heat to process (MW)	141	142.5	59.2	130.15	244.5	150.2	171	65.5	52.6	42.4
Power-to-heat ratio	0.4	0.30	0.50	0.33	0.04	0.04	0.04	0.07	0.04	0.05
Boiler efficiency (%)	69	68	88	74	69	72	71	70	62	73
Cogeneration efficiency (%)	61	67	73.4	67.4	67.1	67.9	72.5	64.9	73.4	74

[a] The name has changed to OMNICANE. [b] One of Mackay sugar mills. [c] Estimated value based on [31] and 200 days/year is considered in cases where the cane crushing days is not available. [d] The name is not reported. [e] Calculated assuming steam-to-bagasse ratio of 2. [f] Assumed values considering other traditional mills in Brazil

Δh is the change in enthalpy in kJ/kg

Fuel power is calculated from Eq. 4.

$$\dot{P}_f = \dot{m}_f \cdot LHV_t \tag{4}$$

where $\dot{P}_f$ is the fuel power in kW

$\dot{m}_f$ is the mass flow of fuel in kg/s

Power to heat ratio (alpha value) is calculated from Eq. 5.

$$\alpha = \frac{\dot{P}_{el}}{\dot{Q}_{ps}} \tag{5}$$

where α is the power-to-heat ratio

$\dot{P}_{el}$ is the electrical power output in kW

$\dot{Q}_{ps}$ is the heat flow to the sugar/ethanol process, kW

Boiler efficiency is calculated from Eq. 6.

$$\eta_B = \frac{\dot{Q}_B}{\dot{P}_f} \cdot 100 \tag{6}$$

where η_B is the boiler efficiency, %

$\dot{Q}_B$ is the heat recovered in the boiler, kW

The cogeneration efficiency is calculated from Eq. 7.

$$\eta_{\mathrm{co}} = \frac{\dot{Q}_{ps} + \dot{P}_{me} + \dot{P}_{el}}{\dot{P}_f} \cdot 100 \tag{7}$$

where η_{co} is the cogeneration efficiency in %

$\dot{P}_f$ is the fuel power in kW

$\dot{P}_{el}$ is the electrical power output in kW

$\dot{Q}_{ps}$ is the heat flow to the sugar/ethanol process in kW

2 Analysis of operational parameters for efficiency improvement

In this section, some of the potential efficiency improvement technologies presented in Section 1 are analyzed through a comparative study of operation parameters of the sugarcane mills. The different methods of efficiency improvement technologies that are considered in this paper are the following: upgrade to electrical drives, upgrade to high pressure-temperature boilers, and upgrade to CEST technology and bagasse drying. An overview and comparative analysis of some technical operational parameters of selected sugar mills are presented. The comparison is done by using the selected key parameters in order to see what type of relationship exists between parameters of different sugar mills. The main goal with this comparison is to identify the gaps between the performance of the modern and traditional mills.

Some of the key parameters are selected based on information gathered from literature [13, 33] discussing the performance parameters of bagasse-based cogeneration units for comparing different cogeneration technologies. These parameters include power-to-heat ratio, boiler efficiency, cogeneration efficiency, electrical power generation index (power per tonne of cane processed), and steam to bagasse ratio.

2.1 Efficiency improvement due to the replacement of mechanical turbines with electric drives

All the traditional mills presented in Table 2 have mechanical steam turbines. In order to compare the performance of the modern and the traditional mills, power-to-heat ratio and cogeneration efficiency are analyzed. The relationship between these two parameters is illustrated in Fig. 2. As can be seen from the figure, the data for both the modern and traditional mills are sorted in such a way that the cogeneration efficiency and the mill sizes are in decreasing order. It can be seen that there is no direct correlation between the cogeneration efficiency and the crushing capacity of the mills. In comparing mills C and I, for instance, both have a cogeneration efficiency of 73%, but their cane crushing capacities are 425 and 150 TCH, respectively. On the other hand, mills D and E have both a cogeneration efficiency of 67%, but mill D has almost half the crushing capacity of mill E. Mill A has a relatively lower cogeneration efficiency but a larger size than the other three modern mills because the steam data is also relatively lower. This indicates that larger capacity does not necessarily mean the cogeneration efficiency is higher. Comparison of the power-to-heat ratio values of the modern and the traditional mills in Fig. 2 shows that the power-to-heat ratio of the modern mills is higher as expected and owing to the fact that the modern mills export surplus power, which is the result of the steam for power generation instead of driving mechanical steam turbines as is the case with traditional mills.

Comparing the cogeneration efficiency with the power-to-heat ratio value in terms of modern and traditional mills, it can be seen that it is not always the case that the modern mills have higher efficiencies and higher power-to-heat ratios simultaneously. This prompts a further examination into the total power (mechanical and electrical) and heat production of the mills as these are inputs for the cogeneration efficiency. Accordingly, referring to Table 2, the four mills that do not have mechanical turbines (mills A–D) generate more turbine power totally than the mills having mechanical power turbines. These four mills also generate excess electrical power and operate at higher steam pressures. In addition, the heat utilized by the mills with electric drives (mills A–D) is relatively lower than the rest of the six traditional mills shown in Fig. 2. These modern mills export power to the grid and the cogeneration unit produces more power than the thermal heat (all mills have higher heat production than turbine power). The other mills (apart from these four mills) have mechanical turbines, and thus, thermal energy consumption is on the higher side as compared to mills A–D. Usually, sugar mills having mechanical steam turbines that drive cane preparation units have higher steam consumption due to the poor efficiency of the mechanical steam turbines. Replacement of these turbines with electric drives will improve the electrical power generation since steam will be saved [11, 12].

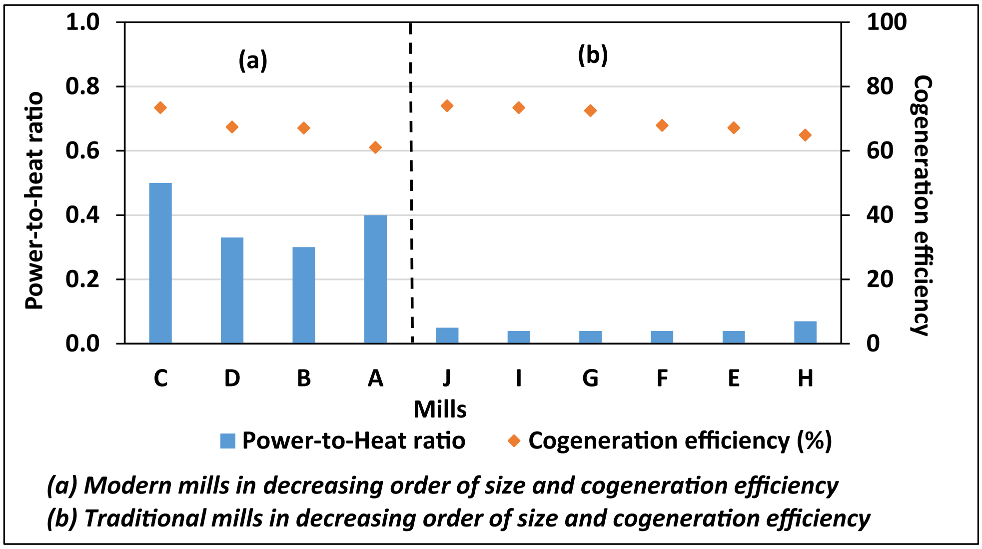


Fig. 2 Comparison of the performance of modern and traditional mills in terms of power-to-heat ratio and cogeneration efficiency

As can be seen from Fig. 2, certain traditional mills have similar or even higher cogeneration efficiency than modern mills. This is dependent on the magnitude of the total heat and power generated per unit fuel power input. For instance, it is seen that the mill with crushing capacity of 125 t/h (mill J) has relatively higher process demand (due to sugar and ethanol production) than the mill with crushing capacity of 425 t/h (mill C) which also requires process heat for sugar and ethanol production, although it has larger crushing capacity. Mill J also produces excess bagasse after meeting the process heat demand and generating electricity for in-house consumption. All the modern sugar mills with surplus power export have both BPT and CEST except the mill C, which uses only condensing extraction steam turbine technology.

It can also be seen from Fig. 2 that the modern mills generate more electrical power (within power-to-heat ratio range of 0.3–0.5) than the traditional mills (within power-to-heat ratio range of 0.04–0.07). These modern mills also generate excess electrical power and operate at relatively higher steam pressures. From an energy utilization viewpoint, the efficiency based on electrical/mechanical power generation is increased with the change to mechanical drives. However, as observed in the cogeneration efficiency comparisons, the total useful energy extracted from each tonne of cane does not in practice become higher with the change to electrical drive. This is a clear indication of underutilized energy potential even in certain modern mills.

2.2 Modification of traditional mills

As can be seen from the analysis in the previous sections, there is a gap between the performance of the traditional and modern mills. Thus, in this section, a conceptual modification of the cogeneration units of the traditional mills for which the mechanical power is available is made. The idea is to bring the performance of the traditional mills up to the standard of the modern mills. The modification is such that three scenarios are considered: case 1, which considers the cheapest and easiest type of modification where BPT and electric drives are installed; case 2, which considers the scenario where HP boilers, CEST, and electric drives are installed; and case 3, which is a combination of case 2 and bagasse drying. Birru et al. [34] had investigated the upgrading of a traditional case study mill to a modern mill by replacing steam turbines with electric drives, implementing bagasse drying and installing a CEST technology. The upgrading concepts and knowledge obtained from that particular study are applied to the traditional mills considered in the current study, though not in detail. Some of the costs such as for the electric drive and the overall efficiency of such drives are also taken from the previous knowledge and applying to the various traditional mills in the current study.

2.2.1 Case 1

The approach used in the analysis of case 1 is to introduce electric motors and back-pressure turbines with a higher installed capacity than the existing turbines of the traditional mills considered. The sugar mills considered are those for which the mechanical power is available (see Table 2) except mill J for which there is an external purchased power input. After the replacement with electric drives, it is considered that the steam used to produce mechanical power is passed through the new BPT in addition to the steam used to generate electric power.

2.2.2 Case 2

The approach used in the analysis of case 2 is such that the total bagasse flow is considered to obtain the maximum steam flow. In this scenario, the mills considered are the same as the ones for case 1. The live steam temperature and pressure of the HP boiler are considered to be 500 °C and 40 bar. The CEST is considered to have one steam extraction point which has the exhaust conditions of the process steam as in the existing mills.

2.2.3 Case 3

The approach used in the analysis of case 3 is such that all the modifications introduced in case 2 and bagasse drying are implemented. The bagasse drying results in reduced moisture content of the bagasse, and this improves the combustion temperature in the boiler. In addition, the steam-to-bagasse ratio improves [35]. For this study, the bagasse is assumed to be dried to 40% MC and the corresponding steam to bagasse ratio is 3 [35]. It is also assumed that for all the modified sugar mills, the flue gas has enough bagasse drying potential.

The surplus power gained after the retrofits implemented under cases 1–3 is compared to select the best-performing case, and this is further analyzed to see the contribution of the surplus power on the current grid power in the specific country under consideration. This is performed by analyzing the current electric power demand, the grid power supplied from electricity generated using different energy sources, and the number of sugarcane mills with no export of power and further investigating the potential contribution of the surplus power from the retrofit. The country-and region-based analysis was primarily targeted on traditional mills that are retrofitted, as the sugar mills in Australia, India, and Mauritius that are considered in the paper are classified as modern mills. Based on the 2015 statistics obtained from IEA [36], the total electrical generation in TWh is 583 for Brazil, 10 for Ethiopia, and 13 for Sri Lanka. Based on the 2015 database obtained from F.O. Licht team [17], the number of sugar mills in these countries for which there is no grid

Table 3 Input parameters and equations for cases 1, 2, and 3

Parameters	Case 1	Case 2	Case 3
Enthalpy (turbine inlet)	T and P from Table 2	500 °C, 40 bar	500 °C, 40 bar
Enthalpy (turbine exhaust)	Same as process steam conditions as the existing mill	Extraction steam has process steam condition as the existing mill Final exhaust @ 0.15 bar	Extraction steam has process steam condition as the existing mill Final exhaust @ 0.15 bar
Bagasse mass flow	Net bagasse flow from Table 2	Total bagasse flow from Table 2	$\dot{m}_{f,\text{new}} = \frac{\left(\dot{m}_{f,\text{net}}+\dot{m}_{f,\text{ex}}\right)\cdot(1-F_{BC})}{1-F_{\text{new}}}$
Steam mass flow	Total steam flow from Table 2	Determined using steam to bagasse ratio in Table 2	Determined using the assumed steam to bagasse ratio of 3
Steam flow to process	Taken from Table 2	Taken from Table 2	Taken from Table 2
Electric power for factory use (existing turbine)	Electric power for factory $\dot{\mathrm{P}}_{\mathrm{el,net}}$ was taken from Table 2	Electric power for factory, $\dot{\mathrm{P}}_{\mathrm{el,net}}$ taken from Table 2	Electric power for factory, $\dot{\mathrm{P}}_{\mathrm{el,net}}$ taken from Table 2
Turbine power output (new turbines)	$\dot{\mathrm{P}}_{\mathrm{el,tot}} = \sum\dot{\mathrm{m}}\cdot\mathrm{h}$	$\dot{\mathrm{P}}_{\mathrm{el,tot}} = \sum\dot{\mathrm{m}}\cdot\mathrm{h}$	$\dot{\mathrm{P}}_{\mathrm{el,tot}} = \sum\dot{\mathrm{m}}\cdot\mathrm{h}$
Mechanical power	Taken from Table 2	Taken from Table 2	Taken from Table 2
Power for electric motors	$\dot{\mathrm{P}}_{\mathrm{el,drive}} = 67\%\cdot(\dot{\mathrm{P}}_{\mathrm{me}} + \gamma_{\mathrm{tr}}\cdot\dot{\mathrm{P}}_{\mathrm{me}})$	$\dot{\mathrm{P}}_{\mathrm{el,drive}} = 67\%\cdot(\dot{\mathrm{P}}_{\mathrm{me}} + \gamma_{\mathrm{tr}}\cdot\dot{\mathrm{P}}_{\mathrm{me}})^{\mathrm{a}}$	$\dot{\mathrm{P}}_{\mathrm{el,drive}} = 67\%\cdot(\dot{\mathrm{P}}_{\mathrm{me}} + \gamma_{\mathrm{tr}}\cdot\dot{\mathrm{P}}_{\mathrm{me}})^{\mathrm{a}}$
Surplus power	$\dot{\mathrm{P}}_{\mathrm{el,ex}} = \dot{\mathrm{P}}_{\mathrm{el,t}}-\dot{\mathrm{P}}_{\mathrm{el,drive}}-\dot{\mathrm{P}}_{\mathrm{el,net}}$	$\dot{\mathrm{P}}_{\mathrm{el,ex}} = \dot{\mathrm{P}}_{\mathrm{el,tot}}-\dot{\mathrm{P}}_{\mathrm{el,drive}}-\dot{\mathrm{P}}_{\mathrm{el,net}}$	$\dot{\mathrm{P}}_{\mathrm{el,ex}} = \dot{\mathrm{P}}_{\mathrm{el,tot}}-\dot{\mathrm{P}}_{\mathrm{el,drive}}-\dot{\mathrm{P}}_{\mathrm{el,net}}$
Heat to process	Taken from Table 2	Taken from Table 2	Taken from Table 2
Fuel power	$\dot{\mathrm{P}}_{\mathrm{f}} = \dot{\mathrm{m}}_{\mathrm{f}}\cdot\mathrm{LHV}_{\mathrm{tot}}$	$\dot{\mathrm{P}}_{\mathrm{f}} = \dot{\mathrm{m}}_{\mathrm{f}}\cdot\mathrm{LHV}_{\mathrm{tot}}$	$\dot{\mathrm{P}}_{\mathrm{f}} = \dot{\mathrm{m}}_{\mathrm{f}}\cdot\mathrm{LHV}_{\mathrm{tot}}$
Power to heat ratio	$\alpha = \frac{\dot{\mathrm{P}}_{\mathrm{el,tot}}}{\dot{\mathrm{Q}}_{\mathrm{ps}}}$	$\alpha = \frac{\dot{\mathrm{P}}_{\mathrm{el,tot}}}{\dot{\mathrm{Q}}_{\mathrm{ps}}}$	$\alpha = \frac{\dot{\mathrm{P}}_{\mathrm{el,tot}}}{\dot{\mathrm{Q}}_{\mathrm{ps}}}$
Cogeneration efficiency	$\eta_{\mathrm{co}} = \frac{\dot{\mathrm{Q}}_{\mathrm{ps}}+\dot{\mathrm{P}}_{\mathrm{me}}+\dot{\mathrm{P}}_{\mathrm{el,tot}}}{\dot{\mathrm{P}}_{\mathrm{f}}}\cdot 100\%$	$\eta_{\mathrm{co}} = \frac{\dot{\mathrm{Q}}_{\mathrm{ps}}+\dot{\mathrm{P}}_{\mathrm{me}}+\dot{\mathrm{P}}_{\mathrm{el,tot}}}{\dot{\mathrm{P}}_{\mathrm{f}}}\cdot 100\%$	$\eta_{\mathrm{co}} = \frac{\dot{\mathrm{Q}}_{\mathrm{ps}}+\dot{\mathrm{P}}_{\mathrm{me}}+\dot{\mathrm{P}}_{\mathrm{el,tot}}}{\dot{\mathrm{P}}_{\mathrm{f}}}\cdot 100\%$

[a] The power absorbed by the mechanical equipment is less than the power produced by the turbines [12]

export reported is 68 in Brazil[1] (See Appendix) and one in Sri Lanka. On the other hand, for Ethiopia[2] based on statistics from 2012 and information reported by Birru [37], three mills with no export of power are considered. The average crushing days per year is taken as 200 for all the three countries.

2.2.4 Model description

Models are built using Engineering Equation Solver (EES). The main equations and input parameters used for building the models are summarized in Table 3.

Assumptions:

- Electric motors have an overall efficiency of 90% including auxiliary losses [34].
- Electrical and mechanical efficiencies of the power turbines are taken as 96% each.
- Based on the finding from Birru et al. [12], the power absorbed by the mechanical equipment such as rollers and crushers is 67% of the mechanical power produced by the steam turbines.
- The isentropic efficiency of the CEST is taken as 75%.
- The discount rate is taken as 6% [38].
- Equipment lifetime is taken as 20.
- The baseline electricity sales price is assumed to be 0.08 USD/kWh.
- Steam-to-bagasse ratio corresponding to 40% bagasse moisture content for case 3 is considered to be 3.0 [35].

2.2.5 Economic analysis

An economic analysis model is built using EES tool, and the levelized cost of electricity (LCOE) is estimated using Eq. 8 [39]. The fuel expense is set to zero as bagasse is free fuel for the sugar mills.

$$\mathrm{LCOE} = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_t^n \frac{E_t}{(1+r)^t}} \left(\frac{\mathrm{USD}}{\mathrm{kWh}}\right) \tag{8}$$

Where,

I_t = investment (installed capital) cost in year t

M_t = operating and maintenance cost in year t

F_t = fuel expense in year t

E_t = electricity generation in year t

r = discount rate

n = number of years

LCOE = levelized cost of electricity in USD/kWh

The number of cane crushing days per season is 200 for all the mills considered in the analysis except for mills G and E that have 167 and 180 days per year, respectively.

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[1] Since the crushing capacity of only some of the mills is reported, an average mill size of 5000 TCD per mill is considered.

[2] An average mill size of 5000 TCD per mill is considered.

In order to annualize the capital investment, a capital recovery factor is calculated from Eq. 9 [39].

$$\mathrm{CRF}=\frac{\frac{r}{100}}{1+\left[1+\left(\frac{r}{100}\right)\right]^{n}} \tag{9}$$

where CRF = capital recovery factor

The capital cost for installing modification equipment is compiled from the information gathered from the literature. Installed cost for biomass CHP technologies with stoker/grate boilers lies in the range 1880–4260 USD/kW [39], BPT installed cost varies from 900 USD/kW for a small system (150 kW) to 200 USD/kW for a larger system (> 2000 kW) [40], electric drives for the shredder and mill rollers costed 215,000 [34], and variable frequency inverters for the electric drives cost (118 USD/kW) [41] and CEST installed costs between 500 and 700 USD/kW [42]. The equipment cost of stoker boilers is taken to be 65% [43] of the average installed costs 1880 and 4260 USD/kW stated above which gives a specific boiler cost of 2000 USD/kW. The electric drive system considered for this study is assumed to cost 150 USD/kW [34]. For biomass-based technologies, the fixed operating and maintenance cost is about 2–7% of the installed cost with a variable O&M cost of 0.005 USD/MWh [39]. The cost of the rotary dryer is estimated to be 250,000 USD for a capacity of 45 t/h [44]. Based on the different bagasse mass flows for the different sugar mills considered in the case 3 modification, the number of bagasse dryers required and thus the cost will be estimated.

The type of modification and cost considerations for the models of the two cases are summarized in Table 4.

2.2.6 Sensitivity analysis

The sensitivity analysis is done using two approaches. The first one considers the variation of the electricity sales price between a minimum of 0.04 and a maximum of 0.16 USD/kWh in order to see its influence on the value of the payback period; the baseline values stated in Table 4 are fixed in this case. The second approach considers the variation of the equipment and the O&M costs for the different cases with the aim of investigating its effect on the LCOE. The summary of the sensitivity analysis and the varied parameters for the second approach is summarized in Table 5.

2.2.7 Results

In order to compare the thermodynamic impact of the three modifications on the original traditional mills, the power-to-heat ratio and the cogeneration efficiencies are used. The results from the analysis are plotted as shown in Fig. 3. As can be seen from the figure, there is an increase in the alpha value from the base case to case 3. This shows more power is generated as the modification becomes more advanced. On the other hand, the cogeneration efficiency shows a more modest increase from case 1 to case 3. There is only a slight difference in the cogeneration efficiency between the base case and case 1 as the total power obtained from the modification in case 1 is not sizeable as compared to the total power obtained from cases 2 and 3. The average increment in cogeneration efficiency values (as compared to base case) for case 1, case 2, and case 3 is 4%, 21%, and 31%, respectively, owing to the fact that more surplus power is generated as the technological advancement improves from case 1 to case 3.

Figures 4 and 5 summarize the model results of the three cases considered for modification of the traditional mills considered. Comparison of the results from Fig. 4 shows that the surplus electric power obtained from case 2 modification is much higher than that from case 1. The surplus power due to the modification made in case 1 and case 2 lies in the range 8–36 kWh/TC and 58–104 kWh/TC, respectively. For case 3,

Table 4 Summary of the modifications and baseline cost considerations for cases 1, 2, and 3

Equipment	Modifications			Cost considerations			
	Case 1	Case 2	Case 3	Case 1[a]	Case 2[a]	Case 3[a]	
				Installed capital cost (USD/kW)	Installed capital cost (USD/kW)	Installed capital cost (USD/kW)	Installed capital cost (USD)
Electric drive	X	X	X	150 [34]	150 [34]	150 [34]	
BPT	X			350 [40]			
HP Boiler		X	X		2000 [39]	2000 [39]	
CEST		X	X		600 [42]	600 [42]	
Dryer			X				Varies[b]

[a] Fixed O&M cost is taken as 1% per year of the installed capital cost and variable O & M costs USD 0.0025/kWh [39]

[b] The cost of the rotary dryer is estimated to be 250,000 USD for a capacity of 45 t/h [44]. This is varied based on the different bagasse mass flows for the different sugar mills considered in the case 3 modification

Table 5 Sensitivity analysis of LCOE

Varied parameter	Equipment									
	Electric drive		BPT		CEST		HP Boiler		Dryer	
	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.
Installed cost (USD/kW)	100	400	300	400	500	700	1880	2100		
Installed cost (10^3 USD)[b]									150	500

[a] Fixed O&M cost (% of installed cost/year): minimum value = 0.5% and maximum value = 2%. Variable O&M cost (USD/kWh): minimum value = 0.0015 and maximum value = 0.005. [b] This is the cost of one dryer (for 45 t/h bagasse flow [44]) and based on the required number of dryers, the total cost varies

the surplus power is the highest owing to the bagasse drying on top of the modifications applied in case 2 and the power generated 102–142 kWh/TC. Similarly, the LCOE is higher for cases 2 and 3 than that for case 1 for all the modified mills. The LCOE value remains constant for case 1, whereas for cases 2 and 3, there is only a slight change in magnitude.

Referring to Fig. 4, a comparison of the surplus power for the modern mills (see Table 2) with that of cases 1, 2, and 3 shows that the surplus power from cases 2 and 3 is on average higher than for the modern mills. A closer look at the equipment in the modern mills A–D reveals that except mill D, the rest three mills have a steam temperature less than 500 °C and in some cases, a steam pressure less than 40 bars unlike the modified mills of cases 2 and 3. In addition, except mill C that uses CEST technology, the rest of the mills uses a mixture of BPT and CEST technologies.

The analysis of the potential of the surplus power generation due to the retrofit of the traditional mills shows case 3 gives the best performance and as such, it is considered in the country context analysis (see Section 2.2.3) where Brazil, Ethiopia, and Sri Lanka are considered. The result of the analysis shows that for the Brazil case (considering the highest surplus power generated by mill J as baseline value), retrofitting 68 sugar mills would give annual surplus electricity generation of 9.6 TWh. This is just under 2% of the total electricity generated in the country. Retrofitting the three mills in Ethiopia and one in Sri Lanka results in a surplus power contribution of 3% and nearly 1% of the total electricity power generated in these countries, respectively.

In order to see the regional contribution of grid power by the sugar mills in Brazil, out of the 68 sugar mills in Brazil, 19 sugar mills located in 9 regions are extracted from Appendix I based on the availability of data for installed grid power in the different regions. The installed power data for these nine regions is gathered from the reports available from ONS [45] and is summarized in Table 6. The region-based analysis of the contribution of the 19 sugar mills to the regional grid power follows the same procedure as the 68 mills and accordingly, one retrofitted sugar mill has the potential to generate the same surplus power as mill J as baseline value (considering the highest surplus power generated by mill J as baseline value). The regional grid power contribution calculation result for the 19 sugar mills is shown in Table 6. As can be seen from the results in Table 6, in most of the regions, the mills after retrofit contribute a surplus power amounting above 30% of the installed power in the respective regions.

Figure 5 illustrates the LCOE and PBP for the three cases. It is based on the baseline electricity sales price of 0.08 USD/kWh, capital cost and O&M costs.

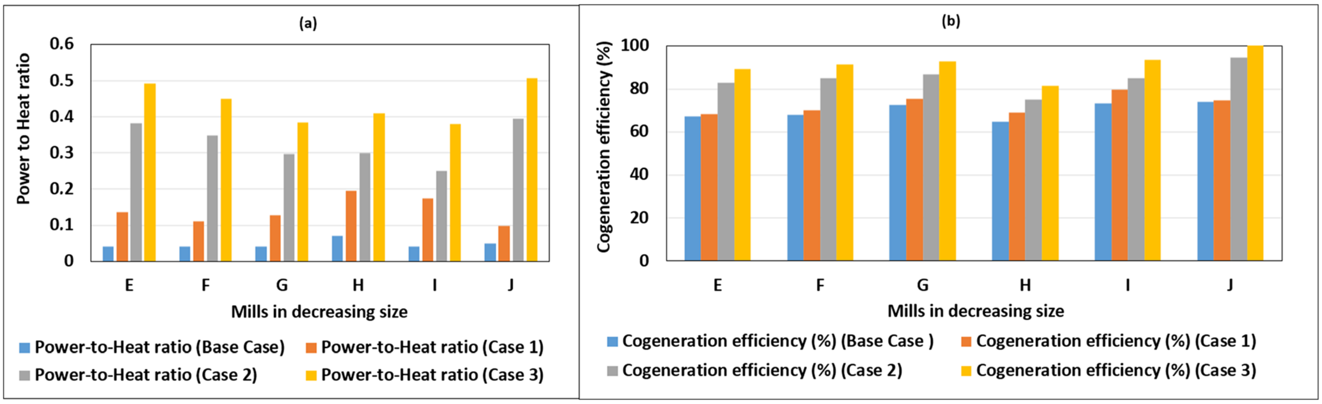
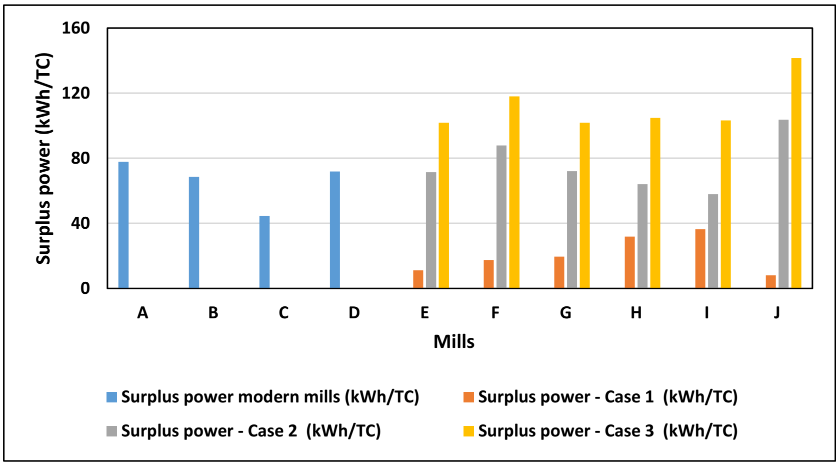


Fig. 3 Comparison of the power-to-heat ratio and cogeneration efficiency for the base case and modified cases

Fig. 4 Comparison of surplus power for the four modern mills in Table 2 and modified mills



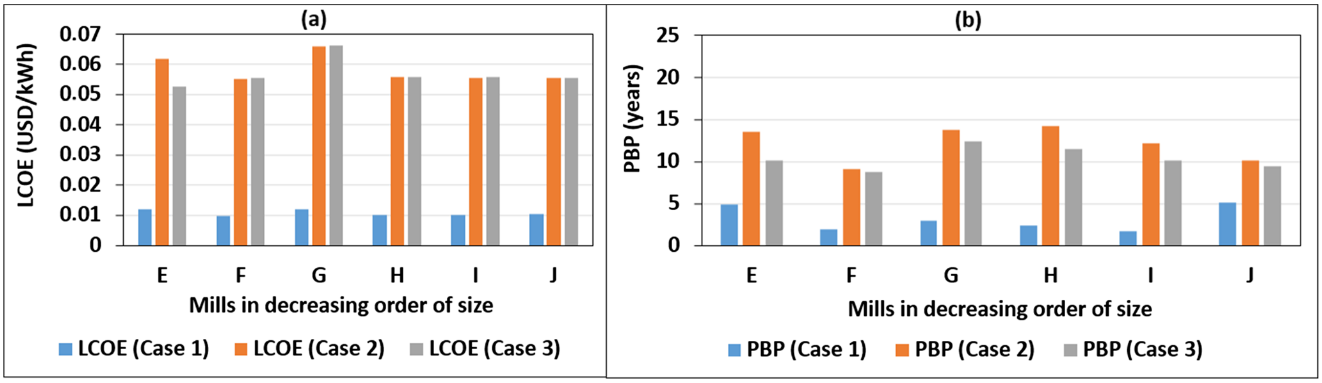


Fig. 5 Comparison of PBP (a baseline electricity price of 0.08 USD/kWh) and LCOE for cases 1–3

Figure 6 shows the sensitivity of the PBP to the variation in electricity price. The PBP of the different mills is averaged for the individual scenarios.

Table 7 summarizes the sensitivity analysis result for the three cases with a fixed electricity price. It can be seen from the result that, there is no change in the LCOE value between cases 2 and 3. On the other hand, the LCOE is sensitive towards the capital cost and O&M costs.

As mentioned earlier, the modification for case 1 is the simplest and cheapest; thus, the investment cost is much lower than for cases 2 and 3. The replacement of the mechanical steam turbines with electric drives resulted in a lower surplus power than obtained from the modifications made in case 2. In addition, the cost of the boiler is the largest cost-incurring equipment in the modifications made in cases 2 and 3; thus, the specific investment cost of case 1 is much lower than that

Table 6 Potential surplus power contribution of retrofitted sugar mills in Brazil to regional grid

Regions	Regional-installed grid power in MW [45]	Potential total surplus power by mills (MW)	Percentage contribution*
Alagoas	277.14	88.2	31.8
Amazonas	437.5	29.4	6.7
Espirito Santo	143	29.4	0.2
Mato Grosso	223	29.4	13.2
Paraiba	224.6	88.2	39.3
Pernambuco	158.77	118	74.1
Rio de Janeiro	342	117.6	34.4
Rio Grande do Sul	318	29.4	9.2
Rondônia	534.6	29.4	55

* This is calculated with respect to the installed grid power in the respective regions

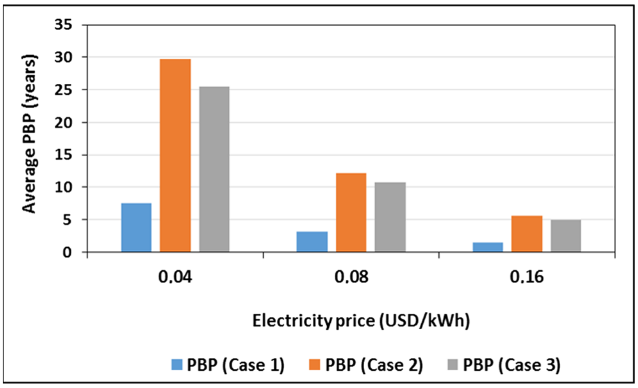


Fig. 6 Sensitivity analysis result for PBP towards electricity price

of cases 2 and 3. Similarly, the addition of bagasse dryer in case 3 and the increased surplus power generated have increased the magnitude of the LCOE.

It is known that most of the sugar mills worldwide are located in developing countries where achieving technological advancement can be a slow process. Therefore, the difficulties in realizing such modifications are associated with several factors. Some of the constrains that hinder practice of such improvements in sugar mills include high capital costs; unstable development of the interest and thereby insecure payback model; seasonality of sugarcane production, thus uncertainty in generating surplus power beyond the crushing season; issues associated with political frameworks; and electricity pricing.

There should be a clear motivation to produce electricity from sugarcane for export to the national grid since the production cost for this generally is lower than from other energy sources in many countries. Still, sugar industry is in many cases not an important provider of electrical energy in other countries where big investments have been performed such as in Mauritius, owing in part to the seasonality of sugarcane production. The retrofit of a sugar mill's cogeneration unit for the purpose of surplus power production may not always be feasible. This is because from electricity sector point of view, year-round supply of electricity is a priority and for state-owned sugar mills—the most common case in developing countries—the electricity tariff along with other institutional barriers and policies makes such retrofit activities unattractive. One example of the effect of electricity price on the investment for a retrofit on the cogeneration unit of a sugar mill is indicated in a study conducted on Carlos Baliño sugar mill [46]. The results have shown that though it is possible to export close to 4 MW of electricity via retrofitting factors like currency rates and the electricity price affect the investment in such a way that increase of costs beyond 10% will reduce the electricity price by the same amount, making such retrofit investment is not feasible. Here, the main constraint for further improvement in Carlos Baliño and other sugar mills in the country is lack of currency for direct investment, since Cuba is in a special situation with the blockade and thus limited possibilities for taking loans abroad.

In the previous study by Birru et al. [34], the remedies in terms of operating the mill in having strategies for the outages were investigated and that required detailed knowledge of that particular sugar mill. However, it is difficult to apply such a detailed analysis for the traditional mills in this study. A further scope for increasing surplus power could be looking for remedies as was done for the traditional mill considered in [34]. It should also be noted that for a proper drawing of conclusions, it is important to know how the mill is operated.

3 Conclusion

In this study, operation parameters of both traditional and modern sugar mills were analyzed with the aim of comparing key-selected parameters which enable to test commonly stated theories for efficiency improvements in sugar mills towards real operation parameters. The comparison of the performance of modern versus traditional mills using the power-to-heat ratio and the cogeneration efficiency has helped to identify the characteristic differences between the two mill types. In addition, the study has included a techno-economic and economic sensitivity analyses for different traditional mill retrofit schemes; the analyses and the results of which can serve as a basis for analysis of larger number of mills and can be applied as reference for performance comparison, respectively. The main conclusions from this study are:

- Traditional sugar mills have higher steam consumption due to the poor efficiency of the mechanical steam

Table 7 LCOE sensitivity analysis result for cases 1–3

	Case 1			Case 2			Case 3		
LCOE ($/MWh)	8	11	17	50	58	72	50	58	72
	Values of varied parameters								
	Min	Baseline	Max	Min	Baseline	Max	Min	Baseline	Max
Capital cost ($/kW)	324	386	497	2395	2623	2861	2399	2630	2868
Annual O&M cost ($/MWh)	0	3	7	4	8	18	4	8	18

turbines which can be improved by replacement with electric drives.

- The size of a sugar mill and the mechanical power consumption are not necessarily proportional.
- Mills without steam-driving mechanical turbines produce more turbine power than those that have such turbines.
- Electricity tariffs among other factors have a significant influence on the decisions related to retrofit activities on the cogeneration units of sugarcane mills.
- High cost-incurring investments like installation of high-pressure boilers may not always be the necessary modification that needs to be made if a surplus power export is required. Other cheaper options such as bagasse drying and replacement of mechanical steam drives with electric ones can be introduced.
- One indication of underutilization of energy potential in modernized mills is that the total useful energy extracted from each tonne of cane does not in practice become higher with the change to electrical drive.
- The retrofit of a sugar mill's cogeneration unit for the purpose of surplus power production may not always be feasible due to, among others, the seasonality of the sugarcane production and the higher costs associated with modern equipment.
- Considering the lower production cost of 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.

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Appendix. Sugar mills located in different regions of Brazil for which export of power is not reported in F.O. Licht database [17]*

Sugar mill owner	City	Region
Grupo Olival Tenorio	*Campo Alegre*	*Alagoas*
Santo Antonio	*Camaragibe*	*Alagoas*
Usina Santa Clotilde S.A.	*Rio Largo*	*Alagoas*
Agropecuaria Jayoro Ltda.	*Presidente Figureido*	*Amazonas*
Infinity Bioenergy	*Vitória*	*Espirito Santo*
Cacu Comercio e Industria de Acucar e Alcool Ltda.	Vicentinópolis	Goiás
Centroalcool S.A.	Cidade Inhumas	Goiás
Grupo Colorado	Morrinhos	Goiás
Grupo Farias	Anicuns	Goiás
Grupo Farias	Itapaci	Goiás
Grupo Jalles Machado	Goianésia	Goiás
Lasa Lago Azul S.A.	Ipameri	Goiás
Usina Goianesia S/N	Goianesia	Goiás
Usina Rio Verde Ltda.	Rio Verde	Goiás
Vale do Verdão	Itumbiara	Goiás
Vale do Verdão	Santo Antônio da Barra	Goiás
Agro Serra	São Raimundo das Mangabeiras	Maranhão
Joao Santos	Coelho Neto	Maranhão
Maity Bioenergia S.A.	Campestre do Maranhão	Maranhão
COOPERB	*Mirassol do Oeste*	*Mato Grosso*
Benedito Coutinho	Nova Andradina	Mato Grosso do Sul
Destilaria Centro Oeste Iguatemi Ltda.	Iguatemi	Mato Grosso do Sul

(continued)

Sugar mill owner	City	Region
Sonora Estancia S.A.	Sonora Estancia	Mato Grosso do Sul
Usina Aurora Açúcar e Álcool Ltda.	Anaurilândia	Mato Grosso do Sul
Agro Industrial de Pompeu S.A.	Pompeu	Minas Gerais
Archer Daniels Midland Co. (ADM)	Limeira do Oeste	Minas Gerais
Cia. Agricola Pontenovense	Urucania	Minas Gerais
Delta Sucroenergia	Conquista de Minas	Minas Gerais
Delta Sucroenergia	Delta	Minas Gerais
Destilaria Antonio Monti Filho Ltda.	Canapolis	Minas Gerais
Ferroeste Industrial	Joao Pinheiro	Minas Gerais
Jatiboca	Sao Pedro dos Ferros	Minas Gerais
PAGRISA	Ulianópolis	Para
Pemel Empreend., Agroind. e Comercio Ltda.	*Recife*	*Paraiba*
Soares de Oliveira	*Mamanguape*	*Paraiba*
Usina Sao Joao (Grupo Ribeiro Coutinho Acucar/Etanol)	*Santa Rita*	*Paraiba*
Coop. Agroindustrial Nova Produtiva Ltda.	Astorga	Parana
Sabaralcool	Perobal	Parana
Acucar e Alcool Bandeirantes S.A.	Bandeirantes	Paraná
Destilaria Americana S.A.	Nova América da Colina	Paraná
Emilio Romani S.A.	Curitiba	Paraná
Sabaralcool	Engenheiro Beltrao	Paraná
Usina de Acucar Santa Terezinha (USACUCAR)	Iguatemi	Paraná
Usina de Acucar Santa Terezinha (USACUCAR)	Rondon	Paraná
Usina de Acucar Santa Terezinha (USACUCAR)	Sao Tomé	Paraná
Colonia Agroindustrial	*Jaqueira*	*Pernambuco*
Inexport Importacao e Exportacao Ltda.	*Escada*	*Pernambuco*
Interiorana Servicos e Construcoes Ltda.	*Estrelliana*	*Pernambuco*
Usina Ipojuca S.A.	*Recife*	*Pernambuco*
Agro Industrial Sao Joao S.A.	*Cabro Frio*	*Rio de Janeiro*
Canabrava Energética S.A.	*Santa Cruz*	*Rio de Janeiro*
COAGRO	*Campos dos Goytacazes*	*Rio de Janeiro*
Companhia Açucareira Paraiso	*Campos dos Goytacazes*	*Rio de Janeiro*
Coop. dos Produtores de Cana Porto Xavier Ltda.	*Porto Xavier*	*Rio Grande do Sul*
Usina Boa Esperanca Acucar e Alcool Ltda.	*Santa Luzia D'Oeste*	*Rondônia*
Alta Paulista Industria e Comercio Ltda.	Junqeirópolis	São Paulo
Biosev SA	Colômbia	São Paulo
Colombo	Palestina	São Paulo
Grupo Farias	Taquarituba	São Paulo
Grupo Furlan	Santa Barbára d'Oeste	São Paulo
Raizen	Araraquara	São Paulo
Raízen	Dois Corregos	São Paulo
Usina Atena	Martinópolis	São Paulo
Usina Zanin Acucar e Alcool Ltda.	Zanin	São Paulo
Vale do Parana S/A Alcool e Acucar	Suzanápolis	São Paulo
Zambianco Acucar e Alcool Ltda.	Pederneiras	São Paulo
TAQUARI Agro Industrial Capela Ltda.	Capela	Sergipe
EQM	Arraias	Tocantins

[*] The italicize regions/sugar mills represent the 19 sugar mills that are located in the regions for which grid power installed capacity is available

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