KTH Industrial Engineering and Management

Sugar Cane Industry Overview And Energy Efficiency Considerations

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Literature Survey document

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Abstract

The increase in global energy demand and environmental concerns is calling for a shift towards using renewable energy sources. Biomass is one of the renewable and carbon neutral energy sources that is being given attention. The slow process in the shift from fossil fuels to bioenergy is because of the bulky and inconvenient forms of biomass for storage and transportation. However, there is an increased interest to convert biomass into easy to handle forms of liquid and gas through the major technological conversion processes available:-thermal, thermochemical and biochemical.

Sugar cane is one major feedstock for bioenergy production. This literature survey is part of a PhD project that focuses on polygeneration in sugar cane industry. The PhD project focuses on assessing the possibilities of employing the concept of polygeneration with the aim of improving the energy efficiency of the sugar mills thereby increasing the services from it.

Advanced power generation systems have a big potential to be integrated into sugar cane factories and thus help generate surplus electricity. Usually, sugar mills having mechanical steam turbines 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.

Keywords: Biomass, sugar cane, bioenergy, polygeneration, modern, traditional, energy efficiency, operation parameters

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1 Introduction

The global demand for utilization or consumption of natural resources has continuously been increasing due to the global economic and population growth. Socio-economic development of a society is considered sustainable if the natural resources are consumed in an efficient, economic, socially and environmentally friendly way. Such sustainable utilization of resources-especially water and energy is a challenge for most societies, in particular for developing ones. This is a challenge due to the fact that there is a limited access to modern energy services in developing societies. This means such societies are far from industrialization, economic growth and improved standard of living. For this reason, efficient utilization of resources is very important in order to have a sustainable development.

Polygeneration, which is an integrated process where multiple outputs are produced from one or more natural resource inputs, is one of the promising approaches that can be used to enhance efficient utilization of resources especially in developing countries. The most common polygeneration systems are: trigeneration systems, gasification systems, biogas generation, water desalination and purification, CO_2 harvesting, and bioethanol industry [1]. Figure 1 illustrates a simple polygeneration system where there are five outputs.

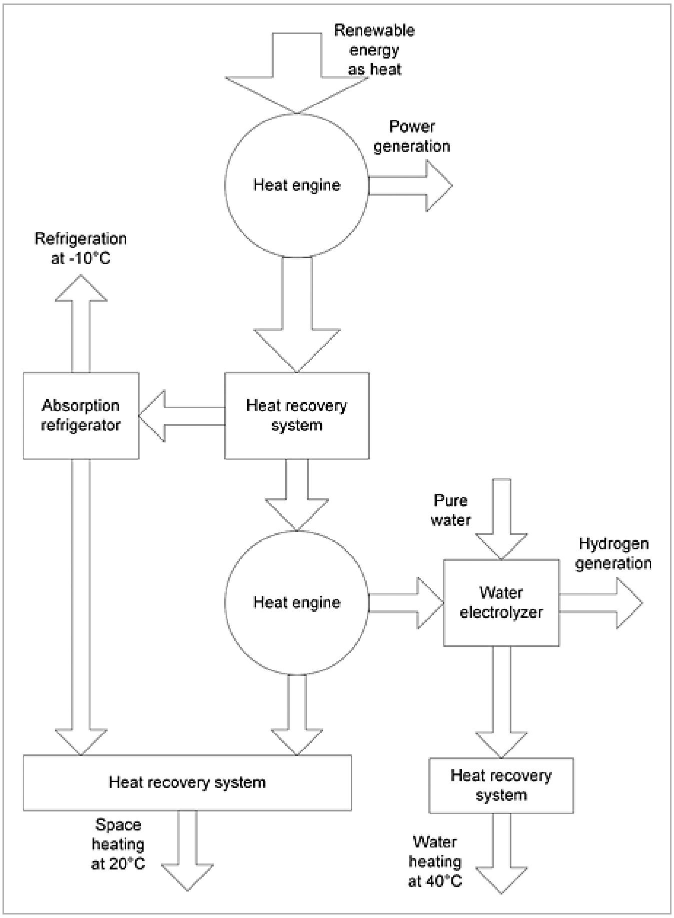

Figure 1 A polygeneration system [2]

One potential producer of energy services that can be considered as a polygeneration unit is the sugar cane industry. This literature survey document is part of the PhD project which focuses on the concept of polygeneration in sugar cane industry. In this study and the PhD project as a whole, what is referred to as polygeneration in sugar mills is depicted in Figure 2 where multiple products are generated from the one common input (i.e., sugar cane).

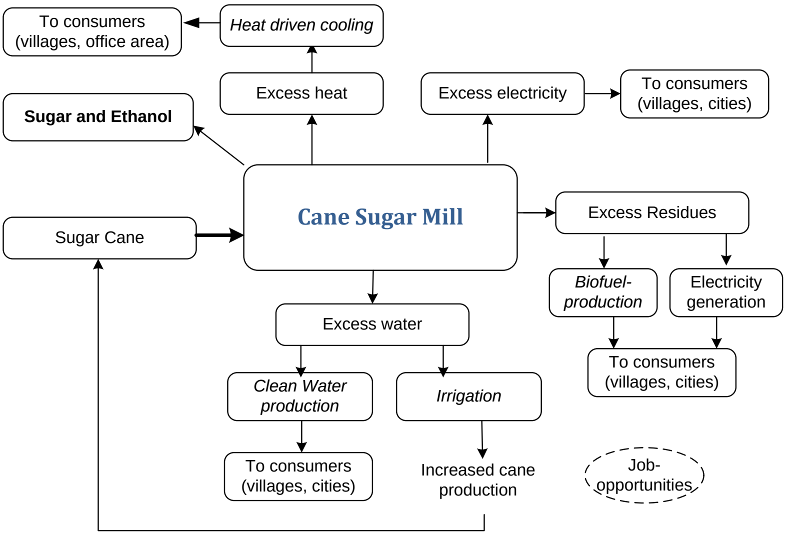

Figure 2: The polygeneration concept behind the PhD project as taken from PhD project proposal document

The task for the whole PhD project is assessing the possibilities of employing the concept of polygeneration with the aim of increasing the energy efficiency of the sugar mills which ultimately will help find out how process integration techniques will increase the services from sugar mills. The polygeneration concept behind the PhD project as illustrated in Figure 2 focuses on the major areas of assessing the potential of:-

(i) Excess power generation
(ii) Excess residues for biofuel production
(iii) Excess heat for district cooling production
(iv) Excess water for recovery

1.1 Objectives

The main objectives of this literature survey are:-

- Providing a brief overview of biomass as an energy source
- Providing an overview and operational parameters of selected sugar cane mills in different countries world wide

- Giving a brief overview of the energy efficiency considerations that are already implemented in sugar cane mills and the potential energy efficiency improvement measures.

Ingeneral, this literature survey document consists of the review of the sugar cane industry worldwide and discusses energy efficiency considerations in sugar cane mills.

2 Biomass as an energy source

Biomass is a biological material that is formed from living plants and animals. The fact that biomass grows through the process of photosynthesis by use of CO_2 and the release of CO_2 upon burning it makes it carbon-neutral. Besides, biomass is a renewable form of energy source unlike fossil fuel which makes it attractive as an energy source. Even though its use as a primary energy resource varies depending on geographical and socioeconomic conditions, biomass has probably been the first to be exploited as a highly demanded energy source [3]. Table 1 shows the sources of biomass.

Table 1 Sources of Biomass [3]

Farm products	Corn, sugar cane, sugar beet,wheat,etc.	Produces ethanol
	Rape seed,soybean,palm sunflower seed, Jatropha,etc.	Produces biodiesel
Lingo-cellulosic materials	Straw or cereal plants,husk,wood,scrap,slash,etc.	Can produce ethanol,bioliquid, and gas

The increase in energy demand and environmental concerns is calling for a shift to the use of renewable energy sources. The slow process in this shift from fossil fuels to renewable energy sources like biomass fuels is due to the fact that biomass has bulky and inconvenient form unlike gas or liquid fuels. The motivation behind for the increasing interest in converting biomass into liquid fuels is because of the easier handling, storage and transportation of liquid fuels rather than the solid form of biomass [4].

The three main types of biofuels produced from biomass are [3]:

- Liquid:- ethanol, biodiesel, methanol, vegetable oil, and pyrolysis oil
- Gaseous:- biogas , producer gas, syngas substitute natural gas
- Solid:- charcoal, torrefied biomass

The major forms of bioenergy, renewable energy derived from biomass, include: heat, power and the three forms of biofuel (solid, liquid and gas fuels). The application areas or end uses of these forms of bioenergy are shown in Figure 3 [4].

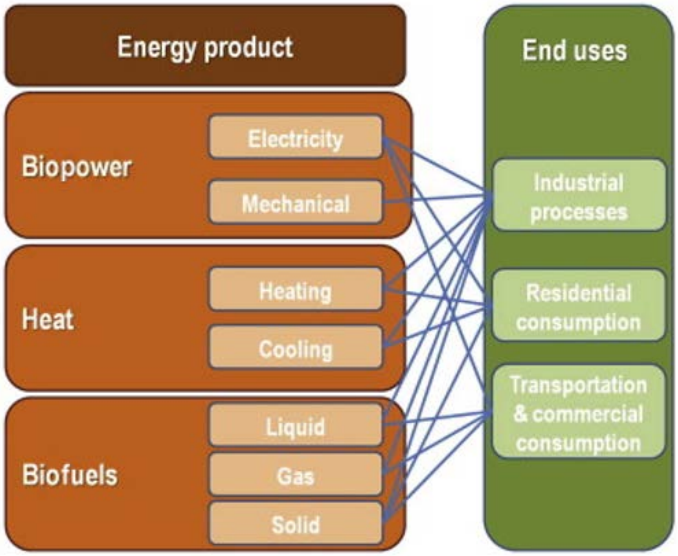

Figure 3 Energy products and their end users [4]

Figure 4 illustrates the three major pathways for the conversion of biomass into the different biofuels. These conversion technologies are: thermal, thermochemical and biochemical [4].

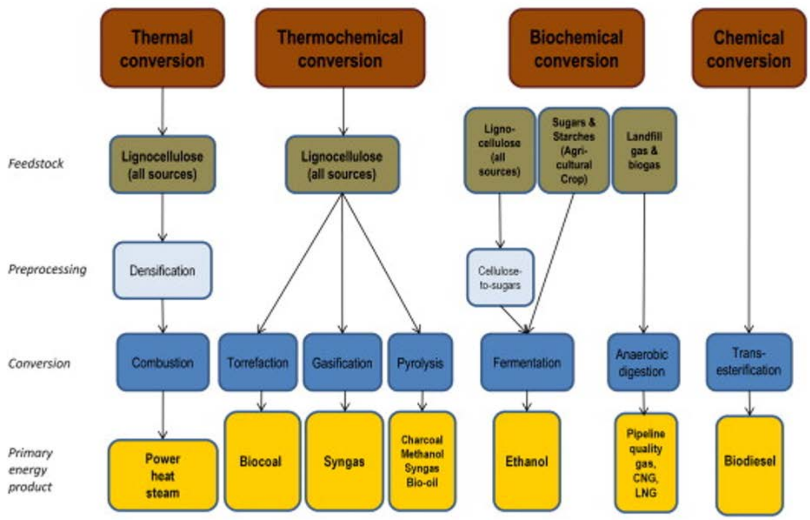

Figure 4 Conversion paths [4]

3 Sugar cane industry-general overview

In this section, a brief general overview of the sugar cane industry is presented. Besides, sugar production process, the concept of cogeneration in the context of sugar industries, energy efficiency improvement concepts in sugar mills and state-of-the-art technologies are briefly discussed.

3.1 General overview

Sugar cane is a kind of grass with big stems similar to bamboo cane and mostly when it is harvested it has a height of about 3m. Sugar cane growth period typically lasts 12 months [5].
As can be seen in Figure 5, out of the total biomass distribution on the sugar cane plant, 60% is millable cane and this has a moisture content of 70-75 %.

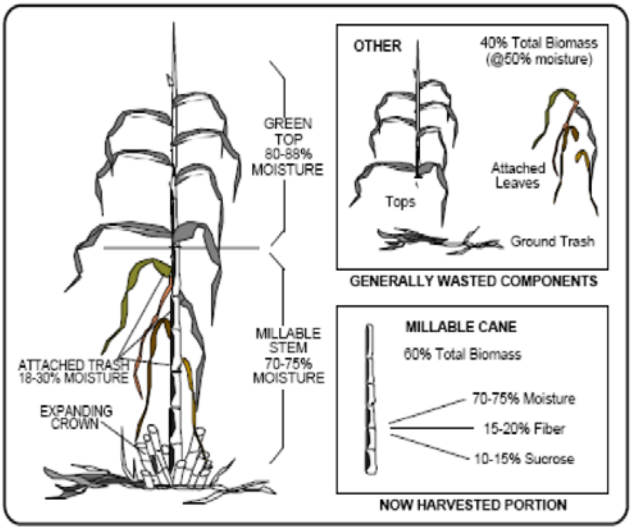

Figure 5 The percentage distribution of biomass on sugar cane plant [6]

Sugar cane is a very efficient energy crop that converts 2 % of available solar energy into chemical energy. Compared to other plants, sugar cane yields the highest amount of calories per unit of area [5]. Sugar cane grows faster than other commercial crops, can be cultivated with sustainable techniques, structural and chemical composition of sugar cane makes it particularly appealing for transformation into valuable products through industrial processing. Table 2 below shows the vegetative structure of a typical sugar cane [7].

Table 2 Vegetative structure of sugar cane (% of dry matter) [7]

Part	**Total Plant (wt %)**	**Part growing above ground (wt %)**
Clean Stalks	50	59
Tops	10	12
Leaves	25	29
Roots	15	- -
Total	*100*	*100*

These fractions in turn have the average composition shown in Table 3. As can be seen above, the agricultural wastes (tops + leaves) represent about 40 % of the total weight. Similarly, the clean stalks are composed of largely soluble sugars and the lignocellulose (fiber) component is what ends up as bagasse.

Table 3 Cane components (wt %)[7]

Components	**Clean stalks (wt %)**	**Tops + Leaves (wt %)**
Total sugars	15.4	2.2
Sucrose	14.1	- -
Lignocelullose (Fiber)	12.2	19.8
Ashes	0.5	2.3
Other	0.8	2.4
Total dry matter	*29*	*26*
Water	71	74

Around 70 % of the global sugar supply is derived from sugar cane whereas the remaining 30 % is from sugar beet [5]. Sugar cane is grown in more than 100 countries worldwide [8]. Figure 6 shows the top five sugar cane producing countries and their sugar cane production in the year 2014 [9]. As can be seen in the figure, Brazil ranks first in sugar cane production globally. Brazil is now the world's leading sugar producer (accounting for about 25 % of global sugar production) and exporter (50 % of world sugar exports) ([8],[10]).

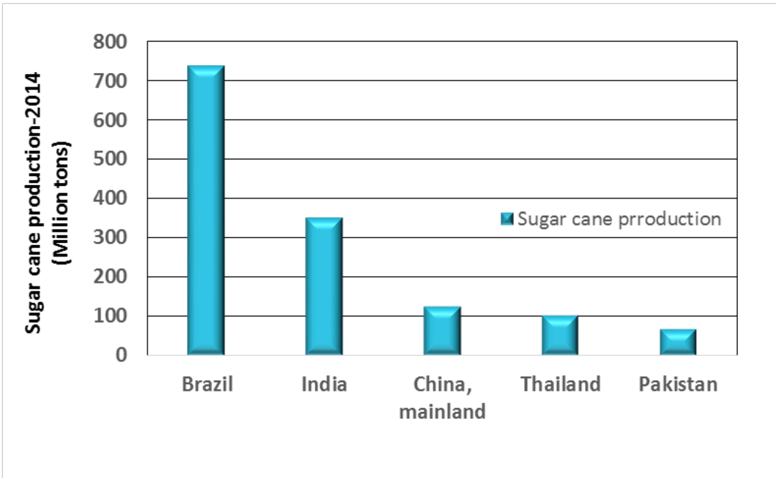

Figure 6 Sugar cane production of the 5 top sugar cane [9]

3.2 Sugar production process

A typical sugar production process involves sugar cane harvesting, cane preparation, juice extraction, clarification, filtration, evaporation, sugar boiling (crystallization), centrifugation and sugar drying. Figure 7 illustrates a simplified production process from sugar cane.

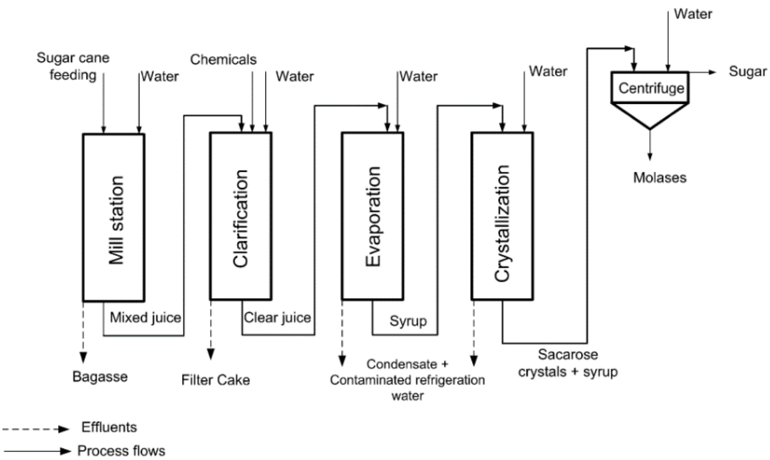

Figure 7 A simplified process of sugar production from sugar cane [11]

A brief description of a typical sugar process is made as follows:

Harvesting: Harvesting of sugar cane can be done either manually or mechanically. Sometimes, burning of sugar cane field is done before manual harvesting, in order to facilitate cutting the cane for field workers. Several countries (E.g. Cuba, Australia and Brazil) are shifting to green harvesting methods [12] as sugar cane field burning causes environmental pollution and loss of the cane straw which contains 30 % of the energy available in the sugar cane plant [13].

Cane preparation: The preparation of sugar cane is a very important step which affects the extraction of juice during milling. Since the sugar content of the sugar cane degrades, the cane needs to be delivered to the milling station in less than 24 hours after harvesting. Before the cane is transferred to the crushing section, it is usually washed to remove dirt that has been transported with the cane from the harvest field. Sugar cane plants use 32-316 liters of water per second and the waste water after the cane washing is either recycled or disposed [14].

Extraction: The next step is to chop up the washed cane in preparation for crushing. This step is skipped if the sugarcane was harvested by machines because it is usually the harvester that cuts the cane stalks into pieces. These chopped up cane stalks are then crushed and milled to extract the sugar juice. Bagasse is produced as a by-product which is usually sent to boilers for burning.

The equipment for milling can involve milling rollers, rotating knives, and shredders (which require additional energy and equipment). For the extraction of the juice from the cane, a process called imbibition is used.

This is a process where water or juice is added in counter current pattern (see Figure 8 below) in order to extract juice as it travels from mill to mill.

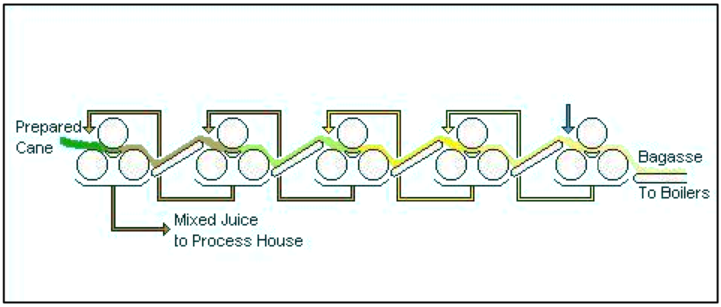

Figure 8 A simplified illustration of sugar extraction process [5]

The juice that leaves the final mill is called mixed juice and its typical sugar content is 15 % (wt %)[5]. Bagasse contains 46-52% moisture, 43-52% fiber and some ash (sand and grit from the field ([5],[15]). A typical sugar cane physical composition can be 12-14% fiber which generates 25- 30 tons of bagasse (50% moisture content) per 100 tons of cane and 10 tons of sugar [5]. During the milling process, cane juice is produced which is the main input for sugar production and ethanol. Not all sugar mills produce sugar and ethanol together. Ethanol is produced depending on the market demand and the mill design. In Brazil however, most of the sugar mills (around 430) can produce both products [8].

<u>Clarification:</u> This involves separation of impurities from the juice by adding flocculants which will react with organic material and precipitation of non-sugar debris (mud) will follow. The clarification process gives clear juice to be sent to the evaporation process and mud which juice will be filtered further [16].

<u>Filtration:</u> This involves the filtration of the mud from the clarification process in order to separate suspended matter and insoluble salts formed (fine bagasse is entrained with these) from the juice ([16],[5]).

<u>Evaporation:</u> The clear juice obtained from the filtration and clarification process will be concentrated to form syrup called molasses by heating it with a low pressure steam in sets of vessels called multiple effect evaporators. The use of multiple effect evaporation is a common practice in sugar mills (typical numbers of effects is quadruple). As can be seen from the stream lines of the single evaporator vessel in Figure 9, primarily exhaust steam (in case of the first vessel) or vapour from previous vessel is fed to a certain vessel. As the juice travels along the vessels it gets more and more concentrated as water is evaporated from it. The vapour obtained from the juice (indicated as 'vapour bled' in *Figure 2.5*) is used in other parts of the sugar/ethanol process [17] or is wasted[14].

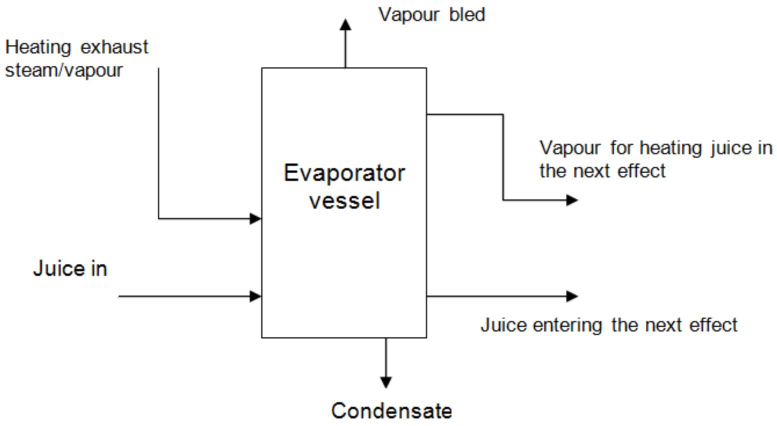

Figure 9 A single evaporator vessel

The parameter juice Brix (expressed in degrees Brix) refers to the weight percent total solids (both sugar and non-sugar) in the juice[18]. The design of the multiple effect evaporators is such that the syrup has 60-70° Brix for raw sugar production and 50-60° Brix for white sugar production. The evaporation process is energy intensive[16]. The principle behind the multiple effect arrangement is that the vapor produced from previous evaporator vessel is fed to the next vessel to evaporate the water from the juice and it is operated at a lower temperature and pressure. The vacuum to be achieved at the last effect is recommended to correspond to a boiling point of 55°C[16]. As stated by Hugot[16], the overall temperature drop (from inlet to outlet of the whole evaporator set) range of evaporation in the multiple effects is 55-60°C which means the difference between 115 or 110 and 55°C in absolute temperatures. The number of effects affects the amount of exhaust steam that is needed to drive the first effect thus more number of effects will result in less exhaust steam needed for the first effect[5].

Crystallization (sugar boiling): This process involves formation of crystals from the syrup which usually takes place in simple effect vacuum pans. The steam for the sugar boiling is usually obtained from the vapor bled from multiple effect evaporators [17] .

Centrifugation: This process separates the crystals from the molasses to get raw inedible sugar. Batch centrifuges are more common in traditional sugar mills but continuous centrifuges are also becoming widely used in newly built sugar mills [16].

Usually in the conventional sugar mills, a set of centrifuges is driven by a system where hydraulic motors having adjustable pumps are driven by motors. The acceleration and deceleration of the centrifuges can be done by adjusting the pumps. In such arrangements, a centrifuge which is being accelerated gets indirectly driven by a decelerating centrifuge as the latter will regain energy as it decelerates and drives a hydraulic motor which in turn enables pumping fluid allowing the pump to act as a motor for the accelerating centrifuge [19].

Drying: This is the final step in the processing of raw sugar before it is packed. The drying process facilitates suitable storage of the raw sugar and inhibits micro-organism development. Prior to drying, raw sugar has a water content ranging 0.5-2% and after drying with hot air the water content can be reduced to 0.2 and 0.5%. Drying is done with air which is preheated with steam. The air should not be heated beyond 95°C-100 °C [16].

Figure 10 illustrates the raw sugar manufacturing as well as the refining process of the raw sugar [20]. The production of refined sugar starts with the washing of the raw sugar with near-saturated syrup and sweet water (i.e., water containing sufficient sugar to remove the thin molasses on the crystal surface). This is followed by centrifugation, remelting of the affined sugar crystals and syrup clarification through either phosphatation or carbonation and decolorization. The clarified and decolorized sugar liquors undergo evaporation and crystallization processes.

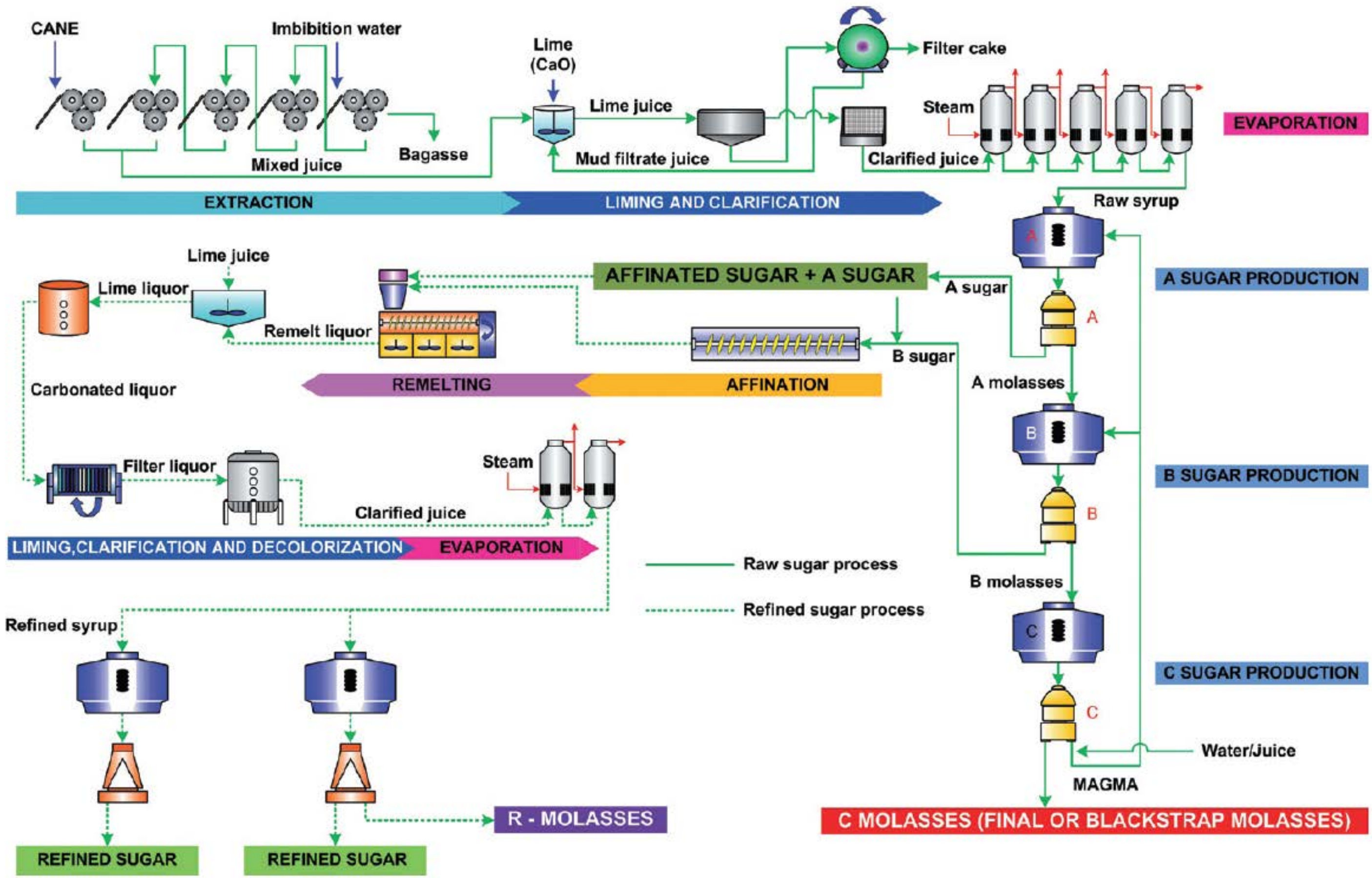

Figure 10 Raw and refined sugar manufacturing process [20]

3.3 Co-generation in sugar cane industries

Cogeneration is a process of producing both electricity and thermal energy (heat and /or cooling) from a common fuel input (See Figure 11 for co-generation from bagasse). Bagasse cogeneration was pioneered in Mauritius and Hawaii. In 1926/27, 26 % of Mauritius' and 10% of Hawaii's electricity generation was coming from sugar mills [21].The total efficiency of the plant increases by about 50% when co-generation is adopted than a separate generation of electricity and power. Traditional sugar mills are self-sufficient in generating their own heat and power even if the co-generation systems of such sugar mills are of low-steam-temperature installations. On the other hand, high efficiency co-generation units equipped with higher efficiency boilers enable surplus electricity generation and allow sugar processing with cheaper heat.

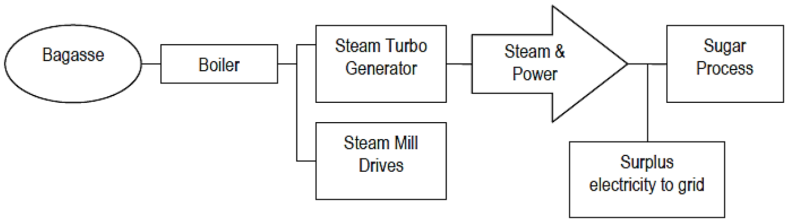

Figure 11 Bagasse co-generation scheme [15]

Regardless of the fact that most mills are energy self-sufficient, the traditional equipment in their cogeneration units are not allowing surplus power production for sales to the grid. Presently, there is an awareness created regarding the advantage of having more efficient cogeneration systems in order to improve the power generation and thus be able to produce surplus power [22]. Traditional sugar mills with no export of electrical power to the grid generally generate 10-20 kWh electrical energy/tc and consume 480-550 kg steam/tc [22]. Modern sugar mills with efficient cogeneration system installations generate electrical energy in the range of 115-120 kWh/tc [22]. Another way of increasing surplus power is by adopting process steam saving techniques. Studies show that reduction of steam consumption from 500 to 350 kg/tc increases the surplus power by 24%. This along with partial use of cane trash will increase the surplus by two folds[21].

3.4 Energy efficiency improvement and surplus electricity generation

In traditional sugar cane mills where backpressure turbo generators are used, the energy contained in sugar cane is underutilized. One reason behind this is that such sugar mills are designed in such a way that they utilize almost all the bagasse they produce for thermal energy and electrical power generation which hinders making use of the energy in the excess bagasse that could have been generated. A typical traditional sugar mill can produce 250-280 kg bagasse per ton of cane processed and this in turn can be used for the generation of 500-600 kg of steam per ton of cane (i.e., about 2kg steam/ kg bagasse)[20]. Another report states that a sugar mill can produce as high as 320 kg of bagasse per tons of cane processed [23]. However, in such mills where back pressure turbines use the sugar/ethanol process as their condensing unit , having excess bagasse in the end of the season is not practical as during off-season there is no possibility to utilize the bagasse for energy purposes if not sold to other stakeholders as a fuel, for example in pellet form [23]. This makes the cogeneration system in traditional mills inefficient as they will be forced to utilize almost all the bagasse they produce. Besides, most sugar cane mills are built as stand-alone units where there is no national grid connection and thus limiting the sugar cane industry to generate surplus power even if the potential for this is present. The other reason why the energy in sugar cane is not fully exploited is due to the fact that, during harvesting of the cane, the cane trash (tops and leaves) which contain 1/3 of the energy contained in sugar cane plant [13] are burned in the field in the case of countries that do not use mechanized harvesting.

The fact that energy demand is increasing worldwide especially in developing countries where sugar cane industries are located as well, looking into the energy potential of sugar mills has been one alternative to address the shortage of energy supply in a form of electric power [24], [25]. Besides, the energy demands of sugar mills themselves have increased as more downstream activities (distilleries, effluent treatment plants, etc.) are being developed. Globally, most traditional sugar mills where modern equipment like high pressure boilers and turbo alternators are not installed are usually self-sufficient in their power generation and in some well operated mills they can even generate excess power during crushing seasons. However, such mills cannot guarantee a year round excess power production which can be exported to the national grid due to the fact that sugar cane harvesting is seasonal.

Introducing more efficient cogeneration systems (basically these are high pressure Steam Rankine Cycle cogeneration systems) ([22],[25]) is the most widely practiced method of generating surplus electric power that can be sold to the national grid, owing to the fact that the steam turbine cycle based cogeneration technologies are well matured and suited to fuels like bagasse. This method has been widely implemented in countries like Brazil [10], Mauritius [21], and India ([21],[26]). Table 4 shows heat to power ratios and typical efficiencies for selected methods for cogeneration in the sugar cane industry. The table shows that as the heat to power ratio increases, the electrical efficiency decreases regardless of the higher total energy efficiency (60%-90 %). In order to achieve higher electrical efficiency, the inlet conditions of the turbine need to be improved. For instance, the cogeneration units of traditional mills have typical live steam parameters in the range of 20-30 bar and 300-400 ^{o}C [15],[17]and[22]. Whereas modern cogeneration units of sugar mills operate with boilers having live steam parameters as high as 45-80 bar (just in few cases around 100 bar) and over 450^{o}C[25]. This indicates that the boiler efficiencies in the modern cogeneration units will improve and thus there is a possibility of generating surplus power owing to the fact that the higher steam parameters of the live steam are to be expanded in the power turbines. The combined use of high pressure boilers with condensing steam extraction turbines, electric drives instead of steam drives, and other steam reduction measures will result in even more surplus power[15],[17],[22],[23] and [27].

Table 4 Heat to power ratios and efficiencies of cogeneration units[27]

Cogeneration system	Heat to Power ratio	Electrical efficiency (%)	Total energy efficiency (%)
Back pressure steam turbine	4-14.3	14-28	84-92
Extraction condensing steam turbine	2-10	22-40	60-80
Gas turbine	1.3-2	24-35	70-85
Combined cycle	1-1.7	34-40	69-83
Reciprocating engine	1.1–2.5	33-35	75-85

3.4.1 State-of-The-Art technologies

Energy efficiency improvement measures in sugar mills can be done both in the cogeneration and the sugar/ethanol processing units. The latter one is not widely practiced as compared to the changes made in the cogeneration units, even though there are several literature studies[16],[25] and [28-31] that state how such improvements can be done. Some of the possible improvements stated in this literature include: steam consumption reduction in the crystallizers, installing continuous vacuum pans, increasing the number of effects of multiple evaporators, use of maximum vapor bleeding in multiple effect evaporators. Regarding energy efficiency measures at the cogeneration unit of sugar mills, there are several case studies and suggestions that state modifications done with the aim of increasing the net electricity production capacity [16], [25] and [32].The most common modifications in the cogeneration units include, installing higher efficiency boilers, introducing more compact and efficient electric drives that replace the conventional steam turbines that produce mechanical power, installing cane diffusers in place of mill rollers in order to decrease electrical power consumption, use of condensing steam extraction turbines together with high efficiency boilers, and bagasse drying. Variable speed electric drives have proved to be a better option for replacing the steam turbines used for mechanical power generation in traditional sugar cane mills ([16],[33]). 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 [16],[25],[27] and [33]. Besides, variable speed electric drives work to match the varying load of cane crushed. It is known that most of the sugar mills worldwide are located in developing countries where achieving technological advancement is 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 large capital costs, unstable development of the interest and thereby insecure payback model, seasonality of sugar cane production thus uncertainty in generating surplus power beyond the crushing season, issues associated with political frameworks, and electricity pricing.

Advanced cogeneration technologies such as biomass integrated gasification combined cycles (BIG-CC)(See Figure 12), biomass integrated gasification with gas turbine (BIG-GT) and Biomass integrated gasification with steam injected gas turbine (BIG-STIG) are in developmental stage thus not a near future solution to improve the cogeneration units of sugar mills. This is due to the fact that gasification of bagasse is not tried at commercial scale [25].

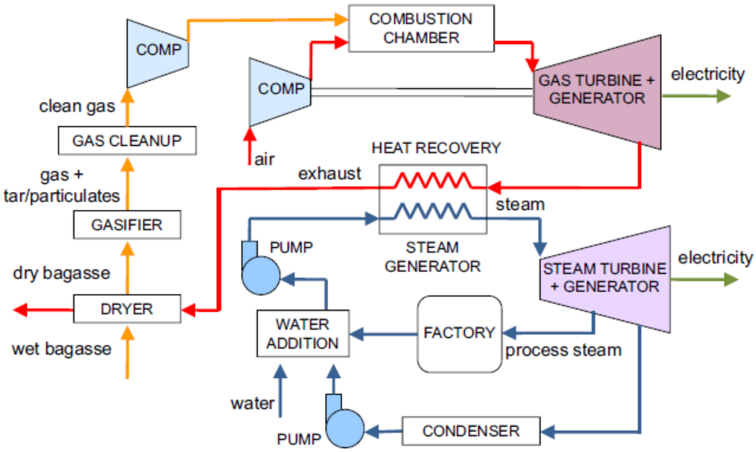

Figure 12 Process diagram of a BIG-CC system for a sugar factory [25]

Studies show that BIG-CC/GT/STIG based cogeneration systems are potentially attractive as they can generate more power than the CEST (Condensing Extraction Steam Turbine) technologies (See Figure 12) ([22],[25]). Kamate [22] states that BIG-CC/GT/STIG systems have a potential to generate up to 270-275 kWh electrical energy/tc whereas sugar mills using condensing extraction turbines can generate 115-120 kWh electrical energy/tc. ISO [21] states that the surplus electrical energy production potential of BIG-GT system is 250-300 kWh/tc and that of the existing high pressure technology is 120 kWh/tc. According to Deshmukh et al.[25], conventional CEST cogeneration systems with 30 bar, 340 °C, and mechanical drives can generate a net electrical energy of 46 kWh/tc and out of this 26 kWh/tc can be exported to the grid. On the other hand, modern CEST cogeneration systems with the same steam parameters but equipped with electric drives, can generate a net electrical energy of 82 kWh/tc and out of this 45 kWh/tc can be exported to the grid. The study also shows that, modern CEST cogeneration systems with higher steam parameters (80 bar,480°C) and electric drives, can generate a net electrical energy of 103 kWh/tc. Out of this, surplus electrical energy can amount 66 kWh/tc. The BIG-CC system, gas turbine is driven by the producer has from the gasification of bagasse and cane trash. The exhaust gas from the gas turbine is recovered in the waste heat recovery unit to produce steam which is used for generating heat and power. The BIG-STIG cogeneration system involves the process carried out in BIG-GT system in addition to steam injection to the gas turbine. 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 off-season by operating the turbine in condensing mode [34].

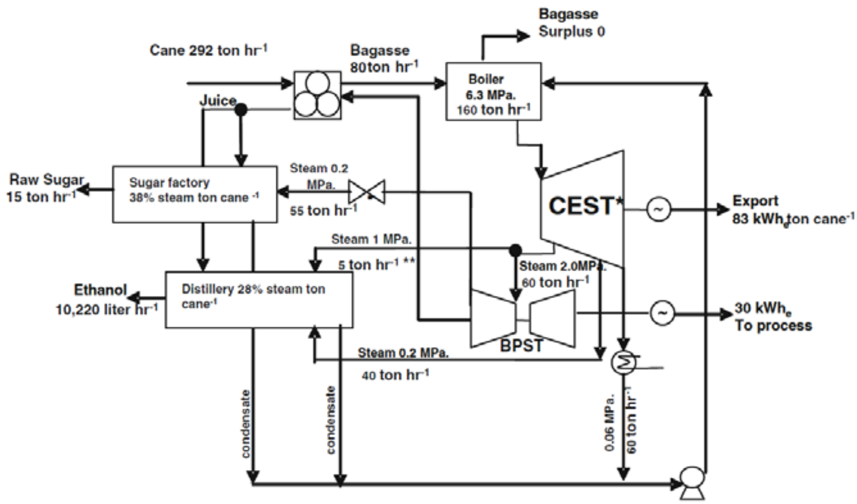

Figure 13 SOTAT (State-Of-The-Art-Technology) sugar mill scheme and cogeneration scheme of condensation extraction steam turbogenerator (CEST). Simultaneous sugar-ethanol production: two extractions (single asterisk) and steam for molecular sieve dehydration (double asterisks) [35]

Figure 13 shows a typical arrangement of the cogeneration plant of a sugar cane mill where surplus power is exported to the grid. The high pressure steam from the boiler is sent to the condensing extraction turbine, the mill driving turbines and the mill turbo alternators. The sugar and ethanol process steam demand is met by the extracted steam from the CEST and the exhaust steam from the other turbines. When high pressure and temperature boiler is installed in such arrangements, export of surplus power is possible owing to the fact that the high efficiency of the boiler results in excess steam in the CEST which is expanded below the atmospheric pressure which in turn increases the power output ([36],[34]).

4 Country overview of sugar industry

In this section, a brief overview of the sugar cane industry of some countries worldwide is discussed.

4.1 Brief overview of the sugar cane industry in selected countries

4.1.1 Brazil

Brazil being the world's leading sugar cane producer owns over 400 sugar mills nationwide and exports sugar to more than 100 countries. Raw sugar export accounts for 80 % and white sugar accounts for the remaining percent of the total sugar export. For the harvest reason 2012/13, sugar cane production was 590 Million tons and ethanol production was 23.2 Million liters[10]. In year 2012, the production of raw sugar in Brazil was 40.2 Million tons [9]. Electric power from sugar cane covers more than 3 % of Brazil's electricity demand. This amount of electrical energy is estimated to cover the power need of an entire country having the size of Sweden or Argentina [10]. In 2009, bagasse-based power generation amounted 4.6 GW with 25 % of this sold to the national grid whereas the remaining balance is used for internal consumption in the sugar mills themselves [17]. Figure 14 illustrates the total primary energy supply for Brazil in the year 2012. As illustrated in the figure, almost 50% of the Brazilian energy mix comes from renewable resources whereas the world as a whole has less than 20 % of the primary energy coming from renewable resources [37].

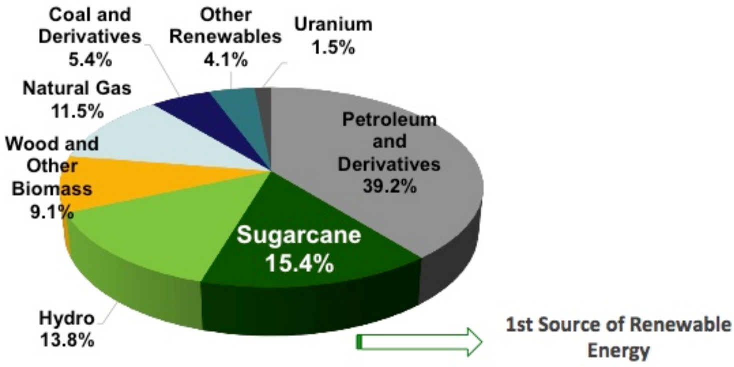

Figure 14 Brazil's energy matrix in 2012 [37]

Sugar cane ethanol has replaced 40% of the country's gasoline need which is sold blended with 18 or 25 % ethanol. The ethanol production of Brazil reached 23.2 billion liters in 2012/13. Due to the customer demand, 90 % of the new cars sold in the country are of flex- fuel [37]. Sugar cane contributes to 15 % of the country's need of primary energy supply[10]. A new research field regarding ethanol production is cellulosic ethanol from cane straw [37]. The first commercial scale second generation cellulosic ethanol has been implemented in the southern-hemisphere by GranBio which is a biotech company in Brazil. The production process involves pre-treatment of straw, enzymatic hydrolysis and fermentation[38]. In general, Brazil achieved replacing half of its petrol demand by ethanol from sugar cane which is grown only on 1% of its arable land. Regarding bioelectricity generation, some of the sugar mills in Brazil are generating surplus power which is sold to the grid. In 2012, 3 % of the electricity demand in the country came from surplus power from sugar mills[37]. Clean Development Mechanism (CDM) implemented in these sugar mills have enabled the generation and export of surplus power to the grid. Sweden has, for example, founded some of these CDM projects. The project design documents for such CDM projects on Brazilian sugar mills is available in the databases found in [39] and [40].

4.1.2 Peru

The sugar production in Peru is in the northern coastlines and is almost year round 11 months, due to the favorable climatic conditions of the coast. The sugar mill shutdown occurs only for one month per year (usually in March) due to absence of cane. Thus the mills need not to be of large size. Almost the entire production of the Peruvian sugar cane crop is in the northern coast. The total milling capacity of these mills is 37 000 million ton of cane per day[41]. 11 million tons sugar cane was produced in 2013 and the world's sugar cane production the same year was 11.9

bllion tons[9]. As can be seen Figure 15, Peru has the highest sugar cane yield per hectare in 2013 as compared to the rest of the world [9]

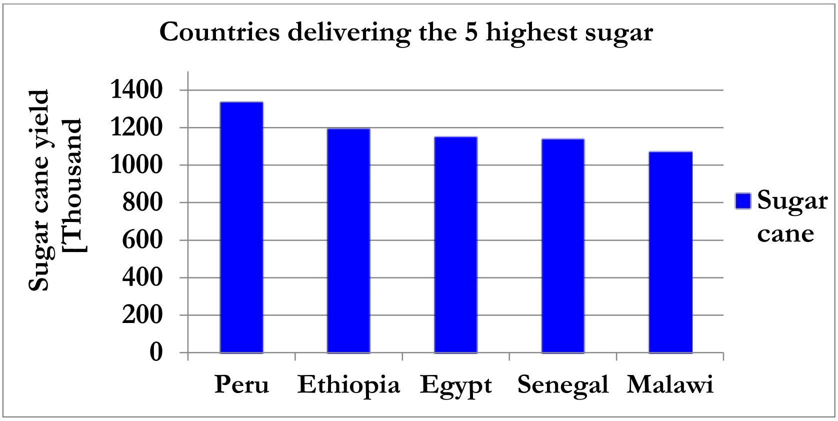

Figure 15 Sugar cane yield of the top 5 producers in 2013 [9]

4.1.3 India

India is the second largest sugar cane producer in the world next to Brazil with its sugar mill sizes varying from 2500 to 5000 TCD with recent plant size expansions of 7500 to 15000 TCD. The installed number of sugar mills is 660 but out of these only 504 were operational in 2010[42]. The sugar production accounts for 15 % of the world's total sugar production. The power export from sugar mills to the national grid is 1300 MW. The mills produce around 2.7 billion liters of alcohol and 2 300 MW power [42]. The number of operational mills in India in 2013/2014 is 509[26]. The surplus power export potential of the sugar cane mills in India is 3500 MW [22]showing the strong potential of bagasse in replacing fossil fuels . This is the potential in addition to the existing surplus power export[21]. India is continually trying to achieve higher amount of surplus power from bagasse cogeneration and the most important strategy behind this move is governmental policy that facilitates the generation, transmission, and sales of electricity. Besides, implementation of CDM projects in Indian sugar mills is also playing a key role[21].

4.1.4 Australia

There are 24 sugar mills in Australia that primarily produce raw sugar and there are four sugar refineries. 80 % of the raw sugar produced is exported overseas making Australia the third largest sugar exporter in the world next to Thailand. In year 2013, 27.1 Million tons of sugar cane was produced in Australia[9]. Most of the refined sugar produced is sold domestically. Typically the sugar mills in Australia are large and the cane crushing season lasts 22 weeks. The crushing capacity of a typical sugar mill in Queensland is more than 500 tons/hr and per crushing season such a mill crushes about 1.45 million tons[43]. The country's largest amount (95 %) of sugar production comes from the county of Queensland. In the year 2012, more than half of the electricity generated in the Australian sugar mills (400 GWh in 2012) was exported to the national grid. The most advanced energy efficiency improving technologies are being implemented in the Australia sugar mills ([43],[44]). Even though the sugar mills in Australia produce raw sugar as their primary product, they also produce molasses based ethanol and electricity [45].

4.1.5 Sri-Lanka

Sugar cane in Sri Lanka is the third most produced crop next to coconuts and rice. In 2013, the production of sugar cane was 700 000 tons and in 2012, the production of raw sugar amounted 36 000 tons[9]. The sugar production trend in Sri Lanka has recently declined comparing the production values over the years 1995 - 2012. The maximum sugar production achieved was in the year 1996 and amounted 74 640 tons[9]. Modern form of sugar manufacture had been practiced in Sri Lanka for nearly 50 years; however, it has never achieved the targeted self-sufficiency production level of 60 %. There are several reasons behind this, the major ones being the closure of Kantale and Hingurana sugar mills having crushing capacities of 2 000 TCD and 1 200 TCD, respectively[46]. The other reasons are lack of expansion of the sugar industry due to government policies, small-scale operation, and poor cane yield. Presently, the plan is to create a profitable, sustainable and productive sugar industry in Sri-Lanka by adopting certain strategies such as : formation of farmers' co-operatives, provision of big cultivation lands to private companies, product diversification, facilitating research, and policy reforms.

4.1.6 Ethiopia

Similar to some sugar cane producing countries in the world, Ethiopia is trying to transform the sugar cane sector into an industry which produces not only sugar and ethanol but also surplus power which can be sold to the national grid. Presently, there are three sugar factories which are undergoing expansion and 5 on-going sugar development projects (these comprise 11 sugar cane mills) in Ethiopia[47]. Table 5 gives statistics compiled from a gathered data obtained from Ethiopian Sugar Corporation office on the existing sugar mills and development sugar projects of new sugar factories in Ethiopia[47].

According to the information obtained from the Ethiopian sugar corporation, the current production of sugar and ethanol in the country (from the existing sugar mills) is 300 000 tons and 18 million litres per year, respectively. The plan is to increase these capacities to 2.25 million tons sugar per year and 181 604 m^3 ethanol within 5 years.

Table 5 Statistics of Ethiopian sugar factories-compiled from [47]

Name of sugar factor/project	Status	Capacity		Cane cultivation area [ha]	Power export [MW]
		Type	Amount		
Finchaa sugar factory	Existing	Cane Sugar Ethanol	5000 TCD 110 000 t/yr 8x10⁶ lit/yr	14 312	0
Wonji/Shoa factory	Existing	Cane Sugar	 75 000 t/yr	8 129	17***
Methara sugar factory	Existing	Cane Sugar	5000 TCD* 136 692 t/yr	8 507**	11***
Tendaho sugar development project	Under development	Cane Sugar Ethanol	26 000 TCD 619 000 t/yr 55.4 x10⁶ lit/yr	50 000	91***
Kuraz sugar development project (5 factories)	Early development stage	Cane	3x12 000 TCD 2x24 000 TCD	175 000	
Welkaiyt sugar development project	Early development stage	Cane	12 000 TCD	45 000	
Tana-Beles sugar development project (3 factories)	Early development stage	Cane	3x12 000 TCD	75 000	
Kesem sugar development project	Early development stage	Cane	10 000 TCD	20 000	

**Obtained from UNDP home page **Obtained from interview with FSF ***Envisaged after expansion*

4.1.7 Cuba

All the sugar factories in Cuba are state owned and most of them do not have annexed ethanol distilleries except 16 mills that produce hydrated ethanol. About 80 % of the sugar cane harvest in Cuba is mechanized [48]. In the first half of the 20th century, Cuba used to be the world's leading exporter of sugar but since 1991 the sugar cane production declined dramatically until 2013 as can be seen in Figure 16. The sugar cane production in the year 2013 was 14.4 Million tons [9]**Error! Bookmark not defined.**.

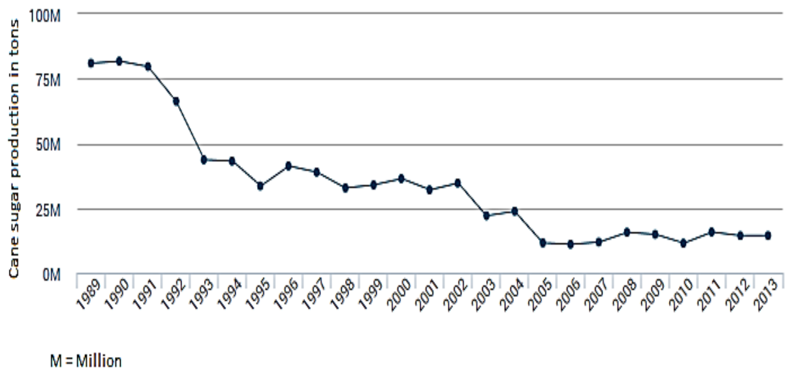

Figure 16 Sugar cane production-Cuba [9]

The major reasons behind the decline in the sugar production in Cuba include the loss of sugar market (due to the collapse of Soviet Union and other communist states in Eastern Europe) and the decline in sugar cane yield (see Figure 17). Many sugar mills in Cuba were previously fired on fuel oil imported from Soviet Union (Cuba used to receive 4 tons of oil for each ton of sugar it exported to Eastern countries in Soviet Union) and not modernized with bagasse boilers, and after this market disappeared, the expensive Cuban sugar could not compete with the rest of the world [48]. The figure clearly shows the deteriorating sugar cane yield between the years 1994 to 2013 as compared to Peru's sugar cane yield (which is the highest in the world in year 2013) for the same duration[9].

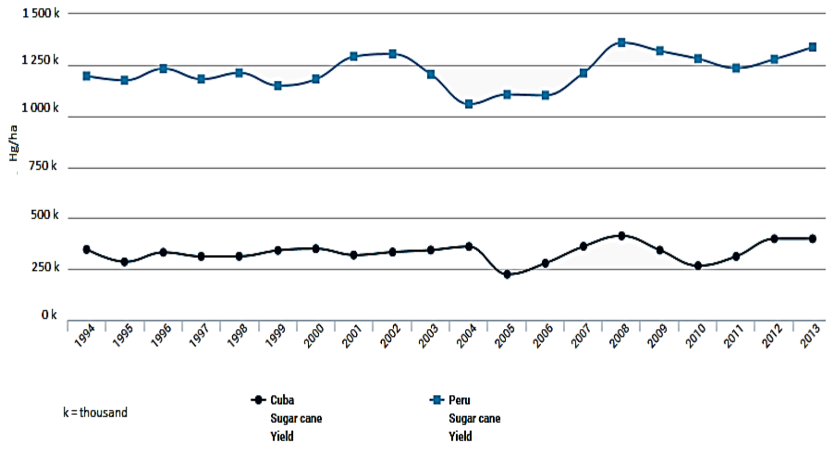

Figure 17 Comparison of sugar cane yield between Peru and Cuba [9]

4.1.8 Mauritius

The sugar cane industry in Mauritius has always played a big role in the country's economy since the time sugar cane had been introduced three centuries ago. The total cane production in 2012 was 3.9 Million tons and the molasses produced was 138 Thousand tons. The raw sugar produced the same year was 4.1 Million tons[9]. Mauritius sugar mills are known to be pioneer when it comes to exporting power to the national grid [49]. In fact, almost all the sugar mills have been upgraded and generate surplus power which is exported to the national grid during the crop season. Bagasse cogeneration systems having steam parameters of 82 bar and 525 °C can produce surplus electrical energy of 75-140 kWh/tc[50]. Some of the sugar mills in Mauritius burn coal during off-season to extend the power production [50]. In Mauritius around 35 % of the sugar cane production is contributed by 30 000 small cane growers. The cane crushing capacities of the 11 sugar mills existing in Mauritius ranges from 75- 310 tons/hr ([49],[50]).

The most efficient bagasse cogeneration systems in Mauritius use high pressure steam of up to 82 bar and temperature of up to 525 °C. Such high efficiency cogeneration units can generate an excess power in the range of 75–140 kWh/tc. The juice extraction mills in Mauritius are mostly equipped with back-pressure steam turbines or electrical motors except one sugar factory where the mills are hydraulically driven [50]. As one part of the legal framework in Mauritius sugar industry, the 10 year plan of the Multi Annual Adaptation Strategy (2006-2015), attempts to reform the existing bagasse cogeneration scheme in such a way that 600 GWh electrical energy is exported from modern mills by 2015[21]. As stated by

ISO[21], one of the strategies to achieve this is to equip all the existing mills with the commercialized state-of-the-art technologies. At present, the average surplus power is 60 kWh/tc[21].

4.2 Sugar cane mill data for some traditional and modern mills

Generally speaking, sugar cane mills are divided into two major categories according to the technology used: conventional (also called traditional) and modern sugar mills. A more detailed explanation on the operation parameters of these two types of sugar mills is discussed in section 3.4. The summary of the characteristics of these two types of sugar mills is explained as follows:-

Conventional (traditional) sugar mills have low pressure boilers, back-pressure turbines, have no surplus electrical power production, have steam turbine driven mechanical equipment (rollers , shredders and pumps), and can have adjacent ethanol distillery but not always.

Modern sugar mills are characterized by high pressure and temperature boiler installations. The co-generation unit of such mills is usually equipped with CEST and thus the production of surplus electrical power is common [51]. Besides, in most modern sugar mills electrical drives are also used in place of steam turbines that produce mechanical power. Modern mills are nowadays introducing diffusers for the cane juice extraction process.

In this section, an overview of some technical operational parameters of selected sugar mills in some countries are presented. Some of the sugar mills are traditional and some are modern mills. Data from 24 sugar mills has been collected to show some key parameters are selected based on information gathered from literature [22], [50] and [52] discussing the performance parameters of bagasse based cogeneration units for comparing different cogeneration technologies. These parameters include: size of plant, heat-to-power ratio, fiber percent of cane (wt. %), sucrose percent of cane (wt. %), sucrose percent of bagasse (wt. %), surplus power generated, boiler efficiency and steam to bagasse ratio.

The parameters summarized in Table 6 are physical performance indicators for four sugar mills located in Africa (and the performance indicators provided are extracted from the reference [50].

Table 6 Some physical performance indicators of sugar mills

Parameters	M1 [53]	M2 [53]	M3 [53]	M4 [50]	M5 [50]	M6[50]	M7[50]	M8 [54]
Cane mass flow rate [tons/hr]	231	91	211	215	304	313	455	125
Fibre % cane	12.86	11.56	13.41	15.3	14.9	13.8	14.6	15.2
sucrose % cane	12.51	12.75	11.59	13.8	13	14	13.9	18.5
Bagasse wt% cane	28.2	26.6	30.6	30.5	31.1	28.7	30.1	34.6
Sucrose % bagasse	3.83	4.32	4.19	1.23	1	1.35	1.39	4.2
Bagasse MC	49.4	50.9	50	48.4	51	50.4	50.2	52.1

According to Hugot[16], factors affecting the milling efficiency include, state of preparation of the cane, specific pressure employed, length of the train (or number of rollers), speed of rotation of the rollers, specific fiber loading, and imbibition.

The fiber percent of cane is one of the two main factors (the other factor being the impurities in the cane juice) that governs the extraction of sucrose from the cane[16]. The standard value of fiber percent of cane is 12.5 % [55] and if it is lower than this, it means we get less bagasse for burning which results in less steam. On the other hand, higher fiber percent of cane than the standard means excess bagasse or excess steam production. It also means that less cane can be milled when there is high fiber content in the cane. From sugar production point of view, what is of interest is the amount of sugar recovered from the cane and this is not always proportional to the sucrose percent in the cane[16].The sucrose content of the cane, no matter how much extraction efficiency there is, will never get fully recovered and thus sucrose losses always occur[52].

Sucrose percent bagasse depends on the milling efficiency, the moisture content of the bagasse and slightly on the sucrose content of the cane.

Tables 7-11 present operational parameters of four sugar mills in Brazil. Table 7 gives operational parameters of a traditional sugar mill with live steam parameters of 21bar and 310°C. The sugar mill generates electric power only for internal use. However, as can be seen in the table, there is an excess bagasse produced (12 tons/hr) which could have been used for excess power generation if high pressure cogeneration installations were adopted.

Table 7 Flow rates, compositions and extraction plant data of Agroval sugar factory in Santa Rita,Brazil sugar mill 8 [54]

Parameters	*Value*	*Unit*
Cane mass flow rate	125	tons/hr
Cane fiber content	15.2	%
Sugar cane content	18.5	%
Bagasse fiber content	43.8	%
Bagasse sugar content	4.2	%
Bagasse humidity	52.1	%
Bagasse mass flow rate	43.3	tons/hr
Total bagasse consumption	19.8	tons/hr
Bagasse burned to process cane	159.1	kg/t cane
Steam bagasse ratio	2	-

Tables 7 and 8 show the major operational parameters of Agroval sugar factory, in Santa Rita, Brazil. There are two power turbines driving generators that produce 1.9 MW of electricity for the factory. The exhaust steam from these turbines has a pressure of 2.5 bar and temperature of 138 °C. The remaining steam is used for generating mechanical power to drive four cane syrup extraction crushers. This steam is expanded in two single-stage direct drive turbines and exits the turbines at 2.7 bar and 180°C. Feed water to the boiler has a temperature of 112 °C [54]. Such operational parameters will help understanding the how the thermal and electrical energy consumption/generation distribution looks like in traditional sugar mills.

Table 8 Turbine drives steam and power conditions of Agroval Sugar factory, Brazil sugar mill 8 [54]

Parameter	*Units*	*Direct drive turbines*			
		Chopper	Shredder	Crushers 1 and 2	Crushers 3 and 4
Inlet temperature	°C	280	277	285	285
Inlet pressure(gauge)	Bar	21	21	21	21
Outlet temperature	°C	171	173	180	178
Inlet enthalpy	kJ/kg	2972.1	2964.7	2984.4	2984.4
Outlet enthalpy	kJ/kg	2807.2	2811.4	2825.9	2821.8
Isentropic exit enthalpy	kJ/kg	2563.7	2558.3	2572.6	2572.6
Turbine shaft power	kW	396	457	448	418
Steam mass flow rate	tons/hr	8.65	10.73	10.18	9.25

Table 9 provides technical data of a traditional sugar mill with live steam parameters of 21 bar and 320°C. The sugar mill generates electric power only for internal use. However, as can be seen in the table, there is an excess bagasse produced (12 tons/hr) which could have been used for excess power generation if high pressure cogeneration installations were adopted.

Table 9 Operational parameters-Brazil sugar mill 9 [13]

Operational parameters	*Value*	*Unit*
Sugar cane crushed/year	2 160 000	tons/year
Sugar cane crushed/hour	500	tons/hr
Amount of bagasse produced	136.8	tons/hr
Bagasse burnt	125	tons/hr
Steam produced	254.1	tons/hr
Steam consumed in the process	492	kg/TC
Live steam pressure	21	bar(g)
Live steam temperature	320	^oC
Process steam pressure	2.5	bar
Steam flow at 1.5 bar(gauge)	187.2	tons/hr
Total power produced	6.5	MW
Power consumed by the plant	6.5	MW
Surplus power	0	MW

Table 10 provides technical data for another sugar mill in Brazil. The sugar mill produces white sugar (230 thousand tons/yr), hydrous ethanol (70 thousand m^3/year), anhydrous ethanol (77 thousand m^3/yr), and inactive dry yeast (1800 tons/yr). The crushing season is effective 180 days. The boiler has steam parameters of 300-315 ^oC and 22 bar.

Table 10 Brazilian sugar mill 10 [56]

Parameter	*Value*	*Unit*
Crushing capacity	21000	TCD
Fibre in cane	11.7	%
Weight of bagasse	275	kg/TC
Moisture in bagasse	51	%
LHV of bagasse	1770	kcal/kg
Pol in bagasse	1.83	%
Excess bagasse amount	49	kg/TC
Excess air in flue gases	35	%
Boiler feed water temperature	118	^oC
Steam to bagasse ratio	2.41	-
Process steam pressure	2.6	Bar
Process temperature	130	^oC
Steam flow to evaporators	217	Tons/hr
Steam to vacuum pans	74	Tons/hr
Steam to power turbines	99	Tons/hr
Steam to Cane knives/shredders	121	Tons/hr
Steam to turbines driving mills	98	Tons/hr

Table 11 gives the operational parameters of a conventional sugar mill in Brazil which produces sugar and ethanol.

Table 11 Base case plant data-Brazil-mill 11 [30]

Parameters	*Value*	*Units*
Cane crushing rate	500	Tons/hr
Bagasse moisture content	50	%
Raw juice purity	86	%
Process steam pressure	2.5	Bar
Process steam temperature	127.4	ºC
Mechanical power demand of cane preparation and juice extraction	16	kWh/t cane
Electric power demand of process	12	kWh/t cane
Exhaust steam pressure	2.5	Bar
Steam for raw juice heating for sugar processing	9.8	kg/s
Steam for raw juice heating for ethanol process	9.8	kg/s
Steam demand for juice evaporation	16.3	kg/s
Steam for sugar boiling	10.5	kg/s
Steam for sugar drying	0.1	kg/s
Steam for fermented liquor heating	8.4	kg/s
Steam for distillation	20.2	kg/s
Total steam demand for sugar and ethanol process	540	kg steam/t cane

Tables 12 and 13 show the operational parameters of Pucalá sugar mill located at the north coast of Peru. The cane crushing capacity is 4800 TCD or 200 tons/hr [40]. In 2003, the effective operation hours per crushing season were 4575 instead of the standard 6000 hours due to machinery and management problems.

Table 12 Electricity consumption -Peru sugar mill 12 [57]

Equipment	*% of electical consumption*	*kWh/TC*	*MW*
Pumps	31.4	11.58	2.32
Cane preparation	21.3	7.85	1.57
Refinement	20.3	7.48	1.5
Distillery	11.9	4.38	0.88
Office and service	9.9	3.65	0.73
Losses	5.2	1.93	0.39

The Pucalá sugar mill has an electrical energy consumption of 36.87 kWh/TC and the thermal energy consumed (including evaporators and crystallizers) is 338 kWh/TC (see Tables 12 and 13). The power turbines are two with 1.5 MW and one with 3.8-5 MW. Besides there is one diesel engine with 1 MW. The average total electrical power generated amounts 3.3 MW. The boiler efficiency is 59 %. The live steam temperature and pressure are 338 °C and 28 bar, respectively. The exhaust steam to both sugar and ethanol processes is delivered at 2.1 bar and 122 -166 °C. The total bagasse flow is 58 tons/hr with a lower heating value of 7.5 MJ/kg . The mechanical energy consumed by cane preparation units is 17 kWh/TC [57].

Table 13 Thermal energy consumption-Peru sugar mill 12 [57]

Equipments	*Mass flow Tons/hr*	*Energy need kWh/TC*
1° and 2° clarification	9.3	30.7
Evaporation	43.1	142.3
Crystallisation	25.3	83.4
Distillation	15.3	256.3
Milling	47.9	50.5
Losses in use	4.75	15.6
Stop losses		15.7

Table 14 shows some operational parameters of the Aruna sugar mill of India [58]. The sugar mill has live steam parameters of 32 bar and 380°C and a cane crushing capacity of 5 000 TCD. The data provided in the table shows that there is an additional power purchased from the national grid.

Table 14 Production data of Aruna sugars & enterprises ltd-sugar mill 13 [58]

Parameter	*Value*	*Unit*
Milling capacity	5 000	TCD
Crushing season	205	Days/year
Downtime	16.3	% milling season
Pol % cane	11.46	% cane
Fiber % cane	14.6	% cane
Process steam pressure	2	Bar
Steam consumption %cane	56	% cane
Bagasse % cane	31.8	% cane
Moisture % bagasse	51.3	%
Bagasse sold	13 334	Tons/year
Installed capacity of power turbines	7.25	MW
Actual power generated	6.25	MW
Power purchased from the grid	70 810	kWh/year
Live steam pressure	32	Bar
Live steam temperature	380	°C

Table 15 gives some of the operational parameters of Thiru Aroonan sugar mill. The Thiru Arooran sugar mill has a single KCP boiler that was installed in 1989. There are air heaters and an economizer associated with the boiler. Regarding power generation, there is a single APF Bellis turbine with installed capacity of 3 MW. The exhaust steam pressure is 1.5 bar. There is no surplus electric power generated by Thiru Arooran sugar mill [58].

Table 15 Production data of Thiru Aroonan Sugars LTD-sugar mill 14[58]

Parameter	*Value*	*Units*
Cane crushing capacity	2 500	TCD
Crop duration	255	Days
Down time	9.5	% milling season
Pol % cane	10.2	%
Fiber % cane	14.50	%
Bagasse % cane	31	%
Moisture % bagasse	50	%
Bagasse produced	155 268	Tons
Bagasse sold to pulp manufacturers and other users	14 682	Tons
Live steam pressure	42.2	Ata
Live steam temperature	400	°C
Boiler capacity	70	Tons/hour
Average process steam consumption	52.5	% cane

Table 16 provides operational parameters of a traditional mill in India having live steam parameters of 21 bar and 343°C. There are nine old and small capacity See boilers with low pressure operation design. Most of these boilers are not equipped with air preheaters and economizers. The electric power generation units are 5 with installed capacities ranging from 1.25 to 2.5 MW and a total installed capacity of 9.3 MW [58]**Error! Bookmark not defined.**.

Table 16 Operation parameters of Vasantdada Shetkari ssk LTD-sugar mill 15 [58]

Parameter	*Value*	*Units*
Cane crushing capacity	5000	TCD
Crop duration	200	Days
Down time	19.4	% milling season
Pol % cane	13.7	%
Fiber % cane	14.3	%
Bagasse % cane	30.8	%
Moisture % bagasse	50.6	%
Bagasse produced	284 422	Tons
Live steam pressure	21	Ata
Live steam temperature	343	ºC
Boiler capacity	13-35	Tons/hour
Average process steam consumption	52.5	% cane
Power generated	9.3	MW

Table 17 shows the operation parameters of a modern plant in India named Ugar sugar mill where upgrading of bagasse cogeneration has been carried out. Four high pressure boilers are used in the existing system and these have a total steam generation capacity of 270 tons/hr. Out of this, two have a capacity of 60 tons/hr each. The third and fourth boilers have steam generating capacities of 70 and 80 tons/hr. All the boilers have a live steam pressure and temperature of 61 bar and 480 °C respectively. There are two power turbines: one extraction cum-back-pressure turbo generators with 22.8 MW capacity and one condensing cum-back-pressure turbo generator with 18 MW capacity. There are two steam extraction pressures for in the process and these are at pressures of 7 bar and 1.5 bar. The sugar mill produces ethanol and exports 30 MW surplus power [59].

Table 17 Operation parameters of Ugar Sugar - sugar mill 16 [59]

Parameter	*Value*	*Unit*
Sugar cane crushing capacity	10000	TCD
Co-generation plant capacity	44	MW
Distillery production capacity	45 000	Lit/day
Total bagasse production	136	Tons/hour
Bagasse for steam generation	128	Tons/hour
Process steam requirement	*240*	*Tons/hour*
• At 1.5 ata (including De-aerator & Dist.)	225	Tons/hour
• At 7 ata (centrifugal and distillation unit)	15	Tons/hour
Total steam generation	270	Tons/hour
Total power generation	44	MW
Power export to grid	30	MW
Power consumption	*34.5*	*kWh/TC*
• Sugar Plant, Dist & Lighting	12	kWh/TC
• Mills	11.5	kWh/TC
• Power Plant	11	kWh/TC

Table 18 shows the major operation parameters of Mackay sugar mill in Australia for both the old plant and the modified plant named in this report as mills 17 and 18, respectively. Mill 17 has a live steam temperature of 260°C and boiler efficiency of 61%. It also generates surplus bagasse. It is equipped with two turbo-generators having 7 MW and 3.5 MW installed power. Mill 18 is the modified set up of mill 17 after a high pressure boiler (64 bar; 510°C) and additional turbine (36 MW installed capacity) have been installed [60].

Table 18 Operating data of Mackay sugar mill - mills 17 and 18 [60]

Parameter	*Factory-no cogeneration*	*Factory with cogeneration*
Crushing rate	500 TCH	500 TCH
Season length	22 weeks (12 % lost time)	22 weeks (12 % lost time)
Fibre	14 %	14 %
Bagasse moisture	51 %	51 %
Boilers	1 X 150 tons/hrtons/hr;17 bar(g);260°C	Decommission
	1 X 180 tons/hr;17 bar(g);260°C	1 X 180 tons/hrtons/hr; 17 bar (g); 260°C (85 %)
		1 X 150 tons/hr;64 bar(g);510°C (MCR)
Boiler efficiency	2 at 61 %	Upgrade retained boiler to 68 %
		New boiler at 70 %
STGs	1 X 7 MW(at 6 MW)	1 X 7 MW (at 6 MW)
	1 X 3.5 MW (at 3 MW)	1 X 3.5 MW (at 3 MW)
		1 X 36 MW (at 34.3 MW)
LP SOC	53 %	45 %
Electric drives	Nil	Shredder;3 X mills; 17 bar (g) boiler
HP/LP make-up	0 tons/hr	0 tons/hr
Surplus bagasse	20 000 tons	Depends on operations

The energy flows of the Pioneer sugar mill before and after modification are found on reference [61]. Table 19 shows some of the operation parameters of the sugar mill based on these energy flows [61]. Mill 19 has a boiler efficiency of 65% and had a power export to the grid of 0.14 MW. The boiler before upgrade [61] had a steam generation capacity of 180 tons/hr and live steam parameters of 18 bar and 270°C. The maximum design pressure of this boiler is 32 bar. After modification of the boiler which involves upgrading of the partial replacement of the boiler parts, the live steam pressure and temperature were increased to 31 bar and 383°C thus the steam generation capacity was increased to 241 tons/hr which allowed generation of surplus power of 44 MW[61].

Table 19 Operation parameters of Pioneer sugar mill before and after modification-mills 19 and 20 [61]

Parameter	*Factory before modification*	*Factory after modification*
Cane crushed	565 TCH	565 TCH
Steam % cane	51.6 steam % cane	39.2 steam % cane
Electric power generated	3.4 MW	61 MW
• Factory	3.26 MW	17 MW
• Export	0.14 MW	44 MW
Boiler efficiency	65 %	69 %
Total steam flow	81 kg/s	62 kg/s
Thermal energy consumed by evaporators, pans and heaters	97 MW	59.5MW

Table 20 provides operation parameters of Pelwatta Sugar mill in Sri Lanka. The information in the table is obtained through email correspondence with the personnel at the Lanka Sugar Company Limited. The cane harvest period is from 1st of May to 15th of October. The average values of brown sugar and ethanol production rates are 275 tons/day and 25 000 lit/day, respectively. There are two back pressure power turbines with design capacity of 1.6 MW each. There are four mill turbines and one shredder turbine each with 430 kW installed power. The exhaust steam pressure and temperature are 2.5 bar and 120 ^{o}C, respectively [62].

Table 20 Operation parameters of Pelwatta Sugar mill-mill 21 [62]

Parameters	*Value*	*Unit*
Cane crushing rate	150	Tons/hour
Steam production	62-65	Tons/hour
Moisture in Bagasse	50-51	% of bagasse
Low calorific value of fuel bagasse	1850	kcal/kg
Pol % in bagasse	2.64	% of bagasse
Live steam pressure (working)	28	kg/cm^2(gauge)
Temperature of the superheated live steam	380$\pm$	^oC
Feed water temperature (at boiler inlet)	105	^oC
kg steam produced/kg bagasse	1.75	kg/kg
Steam consumption of quadruple effect evaporator	60-65	Tons/h
Steam consumption of batch pan and continuous(1st vapor)	34.5	Tons/h
Boiler efficiency (LHV basis)	62	%
Bagasse (2 nos of Yoshimine boiler available, fuel consumption of each 20500kg/h)	41	tons/hr
Fuel oil (two Yoshimine boilerss available, fuel consumption of each 3762kg/h)	7.5	kg/h
Electrical power generation	2.5	MW

Table 21 gives the operation parameters of Finchaa Sugar Factory (FSF). The factory is located at 385 km from the capital city of Ethiopia Addis Ababa and was commissioned in 1998. During the cropping season, FSF can provide electricity to the sugar mill and also to part of the irrigation pump stations, the surrounding towns and villages (around 1.16 MW power)[63]. The average annual production capacity of FSF has reached 110 000 tons of sugar and its ethanol production is around 8 million liters per year. The factory has around 16000 hectares of sugar cane plantation with a planned expansion to 21000 hectares of land. The factory has undergone an expansion project with the aim of upgrading the existing 5000 TCD (ton cane per day) plant to 12000 TCD and the extended part has started operation in 2013[47].

The nominal operation parameters of the old plant before expansion is provided in Table 21 are gathered from field study and daily records of operation parameters of the factory. The total bagasse flow at 50% moisture content is 15.2 kg/s and the excess bagasse is 0.14 kg/s [6]. Based on the information gathered from FSF [64], the average furnace oil consumption for the crushing seasons (2006/07-2011/12) was consumed at a rate of 1.34 litres per ton of cane as an extra fuel. This furnace oil is used in addition to its usage for startups, during milling stoppages (caused for instance by bagasse conveyor failure) ([64],[65]).

The cane crushing capacity is 4264 TCD which is assessed based on the the total bagasse flow (15.2 kg/s) and the average bagasse mass percentage per unit of cane (30.8%) for the crushing seasons (2006/07-2011/12). The average steam percentage cane for the crushing seasons (2006/07-2011/12) (which equals to 56%)[64]. The average value of the steam to bagasse ratio is 1.9 (kg/kg).

Table 21 Operation parameters of FSF-mill 22 [64]

NO.	Parameter	Amount
1	**Cane**	
	Fiber percent cane (%)	14
	Cane crushing capacity (kg/s)	51
2	**Bagasse**	
	Total bagasse flow at 50% MC (kg/s)	15.2
	Excess bagasse (kg/s)	0.14
	LHV_{dry} (kJ/kg)	17800
3	**Boiler**	
	Feed water temperature (°C)	105
	Live steam pressure (bar)	30
	Live steam temperature (°C)	400
4	**Prime movers**	
	Steam mass flow through power turbines (kg/s)	11.47
	Steam mass flow through turbo pumps (kg/s)	2.56
	Steam consumption rate of shredder turbine (kg/kWh)	13.5
	Steam consumption rate of mill turbine (kg/kWh)	13.3

Table 22 provides the major operational parameters of Carlos Baliño sugar mill[66]. The sugar mill is located in Villa Clara, Cuba. It was built in 1903 and in 2001 it started producing organic sugar which accounts for 30 % of its total sugar production. The sugar mill is now known for its high efficiency equipment and high quality product. The cane crushing capacity is 2 300 TCD and the crushing season is between 15th of December to April. The process steam pressure is 2.05 bar.

Table 22 Operation parameter of Carlos Balino-sugar mill 23 [66]

Parameter	*Value*
Electrical power consumption by two motors driving: cutting mill and 3 mills that receive shredded cane	Motor1-400 kW Motor2-400 kW
Electrical power for shredder motors	Motor 1-320 kW Motor2-250 kW
Electrical power consumption by other factory units	2842 kW
Total electrical power consumption	4.2 MW
Boiler capacity	60 tons/hr
Live steam pressure	17 bar (gauge)
Live steam temperature	260 º C
Bagasse MC	50 %
Pol % of bagasse	1.89 %
Cane flow	2 300 TCD
Sugar produced (30 % Organic and 70 % conventional sugar)	15 000 t/year

Table 23 gives operation parameters of Savannah sugar mill after CDM project had undertaken at the sugar mill with the purpose of increasing the surplus power generation. The factory has a live steam pressure and temperature of 82 bar and 525°C with a surplus power generation of 67 MW [67].

Table 23 Design operation parameters of Savannah sugar mill-modified plant-sugar mill 24 [67]

Parameters	*Value*	*Unit*
Cane crushing capacity	425	tons/hr
Crushing hours per season	6369	h
Total bagasse flow	56.5	tons/hr
LHV of bagasse	7500	kJ/kg
Total steam flow	130	tons/hr
Live steam pressure	82	Bar
Live steam temperature	525	^{o}C
Process steam pressure	2.7	bar
Process steam temperature	140	^{o}C
Feed water temperature	130	^{o}C
Process steam flow	99.1	tons/hr
Total electrical power generated	28.1	MW
• Export	67	%
• For power plant consumption	11	%
• For sugar factory	22	%

Table 24 summarizes the key parameters of the previously discussed sugar mills.

Table 24 Summary of key comparison parameters for the selected mills

Parameter	Mill 8	Mill 9	Mill 10	Mill 11	Mill 12	Mill 13	Mill 14	Mill 15	Mill 16	Mill 17	Mill 18	Mill 19	Mill 20	Mill 21	Mill 22	Mill 23	Mill 24
Cane crushed [tons/hr]	125	500	875	500	200	208	104	208	417	500	500	565	565	150	178	96	425
Total bagasse [tons/hr]	43	137	241		58	66	32	64	136	132	132			41	55	29	57
Net bagasse [tons/hr]	33	126	198	135	58	64	30	64	128	126	132			41	54	29	57
Excess bagasse [tons/hr]	10	12	43			3	2	0	8	5	0	0	0	0	1	0	0
Total steam flow [tons/hr]	67	254	396	270	98	121	54	109	270	330	330	292	223	82.0	103	60	130
Mech power [kWh/TC]	14	9	23	16	17									14	18		
Steam to process [tons/hr]	67	246	396				54	109	240	265	225	292	223	82.0	103	60	99
Total el power [MW]	2	7	9	6	7	6	3	9	44	9	52	3.4	61	2.2	5	4	28
El power for factory [MW]	2	7					3	9	14	9	9	3.3	17	2.2	5	4	9
Surplus power [MW]	0	0					0	0	30	0	43	0.14	44	0	0	0	19
Live steam T [°C]	290	320	300	320	338	380	400	343	480	260	260 & 510	270	383	380	400	260	525
Live steam P [Bar]	22	22	22	22	28	32	42	21	62	18	18 & 64	18	31 & 66	29	30	18	82
Steam to bagasse ratio	2	2	2	2	2	2	2	2	2	2	2			1.75	2	2	2
El power consumed [kWh/TC]	15	13		12	37	30	29	45	34	18	18	5.8	30	15	27	44	22
El power generated [kWh/TC]	15	13	10	12	17	30	29	45	106	18	105	6.0	108	15	27	44	66
Heat to process [kW]	42399	150197	244485	170970	59589	75141	34300	68863	130510	208963	208963	97000	59500	52594	65498	37800	59240
Heat -to- Power ratio	22	23	27	28	18	12	11	7	3	23	4	29	1	24	14	9	2
Boiler efficiency [%]	73	72	69	71	60	68	68	60	74	61	68	65	69	62	70	72	88
Boiler 1						71											
Boiler 2						65											
Power purchased [kW]					yes	14			0	0	0	0	0				0
Steam percent cane [wt %]	54	51	45	54	49	58	52	52	65	53	45	52	40	55	56		31
Fuel oil [tons/hr]														8	0		0

From Table 24 it can be seen that all the mills except Mills 16, 18, 20 and 24 have mechanical steam turbines. However, not all the mechanical power consumption values are available for the mills having mechanical steam turbines. Comparing the total electric power generated for both the mills that have mechanical turbines and those that do not have these, it can be seen that the four mills that do not have mechanical turbines generate more electrical power than the mills that produce mechanical power. These four mills also generate excess electrical power and operate at higher steam pressures. 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.

The heat-to-power ratio of Mills 16, 18,20 and 24 is lower than the rest of the 17 mills and is in the range of 1-4. These mills export power to the grid and the co-generation unit produces more power than the thermal heat. The other mills (apart from these four mills), the heat-to-power ratio ranges from 9 to 32. These mills have mechanical turbines and thus thermal energy consumption is on the higher side as compared to the four mills that do not use mechanical turbines.

5 Conclusion

The main concluding remarks include:-

- The interest in shifting towards bioenergy is increasing globally. Sugar cane is one of the major feedstocks that is being given high attention.
- Consideration of Polygeneration from renewable energy sources like biomass is a promising approach for improved utilization of natural resources especially in developing countries.
- Energy efficiency improvement measures for sugar cane industry can be done both in the cogeneration and the sugar/ethanol processing units.
- Commonly implemented modifications in cogeneration units of sugar mills include:- installing high pressure boilers, use of efficient electric drives instead of the conventional steam turbines that produce mechanical power, use of diffusers for cane juice extraction instead of mill rollers ,use of condensing steam extraction turbines together with high efficiency boilers, and bagasse drying.
- Integrating advanced cogeneration technologies such as BIG-CC in sugar cane mill facilities is considered to be promising as one step forward to producing surplus electricity and efficient utilization of the boiler capacity.
- The heat-to-power ratio of the modern mills generating surplus power is quite low as compared to the mills using back-pressure turbine and not exporting power to the national grid. Higher cane crushing capacity doesn't necessarily result in higher electric power generation. The electric power generation is rather closely related to whether a certain sugar mill has mechanical steam turbines or not.
- A further analysis and comparison of the gathered data from different sugar mills helps to understand the interrelationship between key parameters.
- Most of the literature survey on the two major segments (excess waste water and heat recovery for thermally driven cooling and excess residue recovery) of the PhD project has been done but not presented in this literature survey document.

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