Hindawi
Journal of Energy
Volume 2023, Article ID 5749122, 25 pages
https://doi.org/10.1155/2023/5749122

Research Article

Bagasse Electricity Potential of Conventional Sugarcane Factories

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Received 26 July 2022; Revised 13 November 2022; Accepted 28 January 2023; Published 19 May 2023

Academic Editor: Antonio Messineo

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Sugar industries have huge potential to contribute to the sustainable energy transition through electricity generation and production of biofuels. Sugar-producing countries generate huge volumes of sugarcane bagasse as a byproduct of sugarcane production. In this study, the performance of an operating traditional sugar factory is analyzed for electricity generation and export potential. The study presents characteristics and energy potential of modern and traditional sugar factories. The challenges facing a traditional sugar mill are inefficient boilers, less efficient and back pressure steam turbines, and wasteful and inefficient use of steam turbine drives as prime movers instead of modern electric drives for the mills and cane knives. Others are the use of inefficient and energy intensive cane mill rollers instead of the diffusers which have low energy requirements. It was demonstrated that the cogeneration potential of sugar factory is quite significant but currently underutilized. Sugar factories can make significant contribution towards mitigation of greenhouse gas emission mitigation through supply of green electricity to the public grid. The study showed that the factory uses very old and inefficient boilers aged over 39 years which contributes to poor performance and low electricity generation capacity. Modernization is required to increase the generation and electricity export capacity through investment in new and modern high-pressure boilers, replacement of inefficient back pressure boilers (BPSB) with more efficient condensing extraction turbines (CEST), and reduction of factory steam consumption by electrification of mills and cane knife turbine drives among other measures. This study showed that the 3,000 TCD factory can invest in a 15 MW power plant based on current average factory performance indicators and more if the throughput and overall performance is close to design parameters.

1. Introduction

The sugarcane crop is grown globally under a wide range of climatic conditions, in the subtropical and tropical regions between 35°N in Spain and 35°S in South Africa. The crop has rain requirements of between 1,200 and 1,600 mm/year. If the rain is well distributed, irrigation is not necessary; otherwise, the crop can also be grown under irrigation. There are many sugarcane varieties with different characteristics, but generally, the crop takes 9-24 months to mature for harvest [1, 2].

About 115 countries globally annually produced over 1.9 billion tons of sugarcane in 2020 for production of sugar, paper, and alcohol for the global markets as well as electricity through cogeneration. Sugarcane is grown in the tropical and subtropical regions and is the world's largest crop by production quantity, with Brazil accounting for 40%. About 79% of global sugar production is from sugarcane while the rest is made mainly from sugar beets. In the year 2017–2018, the sugarcane industry was the world's second-largest crop production industry, which emphasizes the significant socioeconomic role of the sugarcane crop industry globally [3–5]. In terms of sugar production, India was the largest producer for the year 2021/2022 producing about 36.88 tons of sugar followed by Brazil at 35.35 million metric tons while the global sugar production stood at roughly 181 million metric tons in 2021/2022 period [6]. The processes in the sugar manufacture and auxiliary services for the plant need continuous and reliable energy supply which can be supplied by bagasse through appropriate cogeneration technology [7, 8]. Besides sugar as the main product in many sugar factories, bagasse contains significant energy potential as a combustion fuel for power generation [9].

Sugar is an important commodity for human consumption and is additionally a vital commodity for socioeconomic development making sugarcane a very important cash crop for many countries [10]. However, sugarcane products are quite vulnerable in the international market, and their prices are quite volatile [10, 11]. The ever growing demand for energy and environmental concerns due to fossil fuel-related greenhouse gas emissions and concerns over the global temperature rise has led to a shift to renewable energy resources. Biomass is an important option being a renewable energy and carbon neutral energy source [12, 13]. Agriculture is an important economic activity with different products adding value to the economies as raw materials for industrial processing or final consumer goods. Sugarcane is an example of a commercial crop used as a raw material for industrial production of sugar and byproducts with significant value addition potential like bagasse and molasses [14]. The sugar factory has become a multipurpose factory simultaneously producing food, energy, and biofuels [15]. As a transition product in the energy and economic transition, sugarcane is used in production of sugar and many other byproducts in more than 100 countries globally [2, 16].

The modern sugarcane industry is diversified and highly integrated producing a wide range of products like sugar, molasses, ethanol, electric power, pulp and paper, charcoal briquettes, and biogas, which remain sustainable and competitive in the market [1, 17]. Bagasse is an energy rich byproduct of a sugarcane factory having significant economic and technical potential for grid power generation [16]. Bagasse-based cogeneration has proved to be a reliable source of grid electricity in countries that have modernized their sugar factories to increase energy efficiency [18, 19]. As evidence from countries with successful bagasse cogeneration like Mauritius, Brazil, and India, development of export-based bagasse cogeneration as a reliable source of grid electricity involves many stakeholders and investment in energy efficient technology and capital in a facilitating legal and policy environment [14, 20]. Several countries like Mauritius, India, and Brazil have the sugar industry connected to the public power grid which earns the industry extra revenue in exchange for clean electricity [1]. India has over 500 sugar factories with bagasse-based power generation of over 3,221 MW [17, 21], while the untapped potential remains more than 5,000 MW [22]. In Brazil, the sugarcane mills are the fourth leading sources of electricity supply to the Brazil's grid electricity mix, even though it is just 15% of the industrial capacity of the sugar industry with estimates showing that sugarcane residues, through bioelectricity can supply 148,000 GWhrs to the grid [23]. In Pakistan, the electricity potential is estimated about 1,598 GWhrs to 2,894 GWhrs [24]. This is an indicator of the huge electricity potential of the sugar cane industry in the global energy transition.

It is generally expected that a sugar factory should be an independent source of energy. This implies that it should produce its own electricity and heat using available materials, mainly filter cake, molasses, bagasse, and trash [25]. Compared to all other crops, the sugarcane crop has the highest potential for bioelectricity generation globally [26]. According to [24], one ton of cane bagasse can produce 0.450 MWh of electricity by means of traditional cogeneration technology, whose benefits include contribution to a country's electricity generation capacity and, generation of employment opportunities particularly in rural areas, with significant environmental benefits and economic benefits for sugar-producing countries [24].

Although just 10 countries account for over 80% of sugarcane production, the crop is grown in more than 100 countries globally [21, 27]. The electricity demand for a typical sugar factory is between 20 and 30 kWh/ton of cane processed. A typical traditional and low efficient sugar factory can produce 60 to 70 kWh/tc, but modern and more efficient sugar factories can generate between 100 and 130 kWh/tc operating at higher steam pressure of up to 88 bars [28]. Evaluation of bagasse cogeneration shows that it is as competitive as fossil fuel power plants in performance indicators [27, 29].

The Kenyan sugar industry provides about five million direct and indirect jobs accounting for about 16% of the country's population. The sector also provides a livelihood to over 120,000 smallholder sugarcane farmers who account for about 88% of factory cane deliveries, with the remainder being supplied by the sugar factories themselves from their factory-owned nucleus estates which provides employment more than 40,000 employees. Sugar remains an important food item in all household while refined sugar is a major raw material for many food-based industries creating jobs and creating wealth for the producing as well as importing countries [30, 31]. This shows that the sugar industry has significant socioeconomic benefits and should therefore be supported particularly for developing countries.

Nzoia Sugar was incorporated on 1st August 1975 under the Companies Act as a limited liability company with the Government of Kenya as the majority shareholder owning 98% of shares. Other shareholders are the Five Cail Babcock of France (FCB) and the Industrial Development Bank (ADB) owning the remaining 2% of the shares. The initial milling capacity was 2,000 TCD which was expanded in 1986 to 3,000 TCD and with optimum sugar production of 315 (TS) per day. A plan to expand the capacity to 7000 TCD and 735 TS stalled after the government failed to pay for its contribution of 15% of the cost with funding provided by the EXIM Bank of US [32]. At 3000 TCD, the factory does not enjoy economies of scale like Mumias Sugar Company Ltd., whose capacity is 7000 TCD [1, 2].

For a long time, the sugar industry has been facing stiff completion from cheap imported sugar from low cost producing countries. The factories are often forced to sell their produce at a loss driving them deep into the debt crisis they continue facing. Delayed payments for cane deliveries from farmers and liberalization of the sugar market have made the factories unable to compete leading to receivership of companies like Muhoroni and partial closure of Nzoia Sugar Factory. Many factories are heavily indebted as they make heavy financial losses and dwindling overall performance. The main causes are delayed payment to farmers who are now abandoning cane farming or sell their cane to noncontracted millers, high cost of farm inputs and sugar production, and adverse weather conditions like droughts leading to low production levels. Sugar production alone can no longer keep these companies afloat financially. There is need to diverse operations and product range by sugar factories to supplement their traditional revenue from sugar sales for survival. Ethanol plant is a good start in addressing these issues [4, 20].

This study is aimed at identifying the challenges of cogeneration in a conventional sugar factory using an operating 3,000 TCD (tons of cane milled per day) sugar factory as a case study. The performance of Nzoia Sugar Factory in Kenya was analyzed to give an insight of the cogeneration situation in medium scale conventional sugar factories and define improvement measures to attain capacity to generate excess electricity for export to the grid by modernization of factory design and operations. A review of the operations of the traditional sugar factory is carried out and comparison made between a modern and conventional sugar factory in terms of steam and electricity generation and applications to identify necessary modifications on a traditional or conventional sugar factory to increase its electricity generation and export potential.

1.1. Problem Statement. The global sugar industry is highly competitive as a result of excess production globally and existence of many high-cost and low-cost sugar producers in the market. This makes diversification by high-cost producers necessary to survive by increasing their revenue streams [1, 31]. The consumption of sugar globally was about 185 million tons in 2017/18 with average long-term annual growth of about 2%. Two-thirds (2/3) of this global demand is supplied locally and from regional production, while the remaining one-third (1/3) of the global production is traded internationally as exports and imports to various countries [33]. For countries like Kenya, the main challenge they face is that demand for sugar is kore than supply. The locally produced sugar is also expensive and cannot compete favorably with cheap imports [33, 34].

The challenges facing the sugarcane industry have created a scenario where consumers have to cope with sugarcane supply shortages and high prices of sugar, while locally manufacture sugar cannot compete against cheap sugar imports [1, 31]. The government and other investors have made huge investment in the sugar factories, but they remain uncompetitive with most of them facing cash flow challenges. Several factories including Muhoroni sugar company, Miwani, Ramisi, and Mumias have closed down as a result of financial and operational challenges. The continued deficit and high cost of production remain a threat to the entire sugar industry from cheap imports coming from low-cost sugar producers. Diversification into bagasse cogeneration in addition to ethanol production will provide some financial relieve to the sugarcane millers whose financial position remains constrained [1, 34].

The sugar industry's future is at stake as a result of high cost of production, reducing sugar prices, and globalization with trade liberalization. These changes have a negative impact on the sugar industry which calls for changes like factory modernization, diversification, and wider exploitation of the sugar factory byproducts for more value-added products for long-term sustainability of the sugar industry [35]. Figure 1 shows average cost of sugar production by eight COMESA (Common Market for Eastern and Southern Africa) member states, which is supposed to operate as a custom union.

As shown in Figure 1, Kenya has the highest cost of sugar production within the COMESA trading block at over USD 450/ton which is more than double the cost of the cheapest producer which is Uganda at about 150 USD/ton [20].

The main challenges facing bagasse cogeneration are as follows:

(i) The energy efficiency of traditional sugar factories is significantly below optimum capacity because of the use of low-pressure steam and inefficient back pressure steam turbines

(ii) Lack of supporting policy initiatives and financing limits the adoption of bagasse cogeneration in many countries

(iii) The sugar industry currently uses only bagasse for cogeneration, yet other resources and products like trash and filter cake have significant energy potential

(iv) The sugar can factory does not operate during out of the crop during which many opt to carry out major maintenance. This means that there is no bagasse fuel supply for the power generation forcing firm power plants to use alternative fuel like coal which is nonrenewable [36]

The main application of bagasse is in steam and power generation for process consumption in juice treatment, fermentation, etc. which requires a minimum of about 50% of the bagasse generated. The excess bagasse is problematic to the conventional sugar factory if it has no alternative application as it leads to safety and health issues like spontaneous combustion and fermentation if stored for a long period of time. It is for this reason that sugar factories deliberately burn excess bagasse mainly by inefficient combustion at the boilers [3, 15]. All sugar factories both traditional and modern have an in-built cogeneration plant, for production of both electricity and heat/steam for internal use [1, 37].

1.2. Rationale of the Study. Sugar production from sugarcane generates significant byproducts like sugarcane bagasse ash, bagasse, molasses, and filter press mud, which can be further processed to economically valuable byproducts in later or downstream processes of sugar production [4]. The global demand for energy resources has been increasing continuously as a result of global economic growth and population increase [9, 38]. Sustainable socioeconomic development requires that natural resources are consumed efficiently, economically, socially, and in an environmentally friendly manner to avoid depletion and environmental degradation [39, 40]. Many countries have limited access to natural resources particularly energy resources making it difficult for the

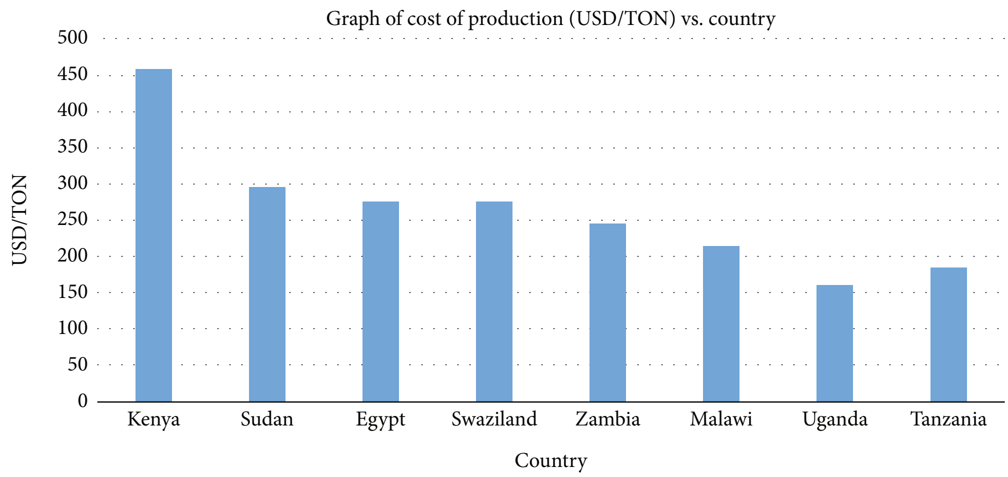

Figure 1: A graph of cost of production per ton in various selected countries.

developing countries in particular to achieve industrialization, sustainable economic growth, and better or improved standard of living. Utilize naturally available energy resources to achieve sustainable energy development [12, 41].

Bagasse is a greenhouse gas neutral fuel whose carbon dioxide produced during bagasse combustion is offset by the carbon dioxide absorbed by the photosynthesis of sugarcane crop. New sugarcane factories should be designed to be energy efficient with significant with the objective of exporting excess power as an additional revenue stream. A typical traditional sugar factory with poor balance between high-pressure (HP) and low-pressure (LP) steam streams vents LP steam due for process use during peak demand as an addition to the back pressure steam from the steam turbine [42]. There are often competing applications for bagasse between cogeneration and the production of high-value byproducts from bagasse like paper and pulp. However, both cogeneration and value addition by sugar factories for bagasse may need some consideration for best technoeconomic application [43, 44].

Bagasse cogeneration is one of the most economically viable options for the agriculture to participate in sustainable power generation and for sustainable development [14]. The green energy can substitute fossil fuels in power generation hence reduce consumption of natural gas, coal, and diesel while at the same time improving the sugar industry competitiveness and sustainability [45]. Since bagasse is a local resource, its use improves energy security and reduces the environmental impact of power generation [46].

Bioelectricity generated by sugarcane biomass has an important role of supplying a sugar factory with required energy mainly in the form of heat/steam and electricity. The energy potential of bagasse can be exploited to generate excess electricity for sale to the grid and generate extra revenue and savings [47]. Therefore, exploitation of the energy potential in bagasse is essential to realize economic sustainability of sugar factories.. Use of alternative energy sources like coal or gas other than bagasse would substantially increase the production cost of sugar [48]. Efficient energy generation and consumption by the sugarcane industry is one of the measures to tackle the challenge of renewable energy access by sugar-producing energy deficient countries. By implementing energy efficiency measures, the sugarcane industry has potential to supply green electricity by efficient use of the bagasse energy potential [49].

2. Literature Review

Agricultural-based industries have significant potential to contribute to the to the sustainable energy transition which seeks to promote the use of renewable energy sources, reduce energy-related greenhouse gas emissions, and increase energy access [38, 40, 50, 51]. Sugar is one of the plants with relatively high bioconversion efficiency of capture of solar energy through photosynthesis with ability to about 55 tons of dry organic matter per hectare of land under sugarcane production annually [35]. The global production of sugar yields about 565 million tons of bagasse per year which is used to meet the energy needs sugar factories and with significant potential for excess generation for sell to the grid [14]. The traditional practice of cane harvesting transfers about 50% of the dry matter as cane stalk to the sugar manufacturing factory for sugar recovery which leaves behind bagasse, as the fibrous left over material of juice extraction process [1, 35]. Sugarcane and corn/maize are few crops which can readily be integrated with cogeneration at commercial scale [11]. Bagasse provides an economically viable options for sugar factories to participate in the energy sector to supply both heat and electricity through cogeneration. Bagasse cogeneration will increase the share of renewable energy in the generation mix, enhance energy access, and increase energy security while supporting climate mitigation efforts and the realization of sustainable development goals [14, 39, 52].

An energy audit of a conventional sugar factory exposes a sugar factory as an industry where energy is intensively used, but at the same time, a lot of energy is wasted. There is a great need for more efficient use of energy resources to maximize overall energy efficiency of sugar mills that help reduce global greenhouse gas emissions from the energy sector. Many studies have shown that energy efficiency in sugar factories can significantly be increased by maximizing electricity generation and minimizing power and factory steam consumption to have enough power for export by generating using more efficient condensing extraction steam turbines [49].

2.1. Global Sugarcane Production and Cogeneration Potential. Sugarcane is a grass with a big stem similar to bamboo cane and often grows high about 3 m. The growth period of sugarcane varies with cane variety and climatic conditions but varies from 12 months to 18 months [1, 12]. About 70-75% of a millable sugarcane plant is moisture, with the remainder being sugars (sucrose and other sugars) and cane fiber or bagasse [12]. Sugar is made commercially from sugarcane and sugar beets which are important cash crops that are among top ten in value internationally. Of the total global production about, 70% of the global sugar supply, which is over 120 million tons per year, is made from sugarcane, while the remaining 30% is made from sugar beets [11]. Over 1.7 billion tons of sugarcane is produced globally in more than 100 countries with almost all factories generating own energy through bagasse cogeneration. Cogeneration is more advanced in countries like as Brazil, Mauritius, and India where a number of factories meet their own energy demand and sell excess to the pubic grid. Sugarcane is grown in many countries globally for sugar production along with other by production like bagasse for electricity generation and molasses for ethanol and other value-added products. The supply of cane as a feedstock for power generation is however limited to the crop harvest season [53].

Brazil is the largest producer of sugarcane globally, accounting close to 25% of global sugar production and 50% of global sugar exports. The country has got many sugar mills involved in surplus power generation as source of extra revenues from electricity export and consequently making bagasse electricity an important component of the electricity mix. This has been motivated by the fact that many developing countries, Brazil included, have shortage of sustainable energy supply and look into the sugar industry for extra power production addressing the shortage of power generation [11].

Energy potential of the sugar industry is dependent on energy efficiency measures in sugar mills to enhance cogeneration and in the sugar/ethanol production so that maximum excess power remains for export to the grid. Both process operations and cogeneration should be improved for maximum energy generation by the sugar mill [2]. Some of the possible improvements include the reduction in steam consumption, by crystallizers, use of continuous vacuum pans, replacement of cane mill rollers with diffusers, increase in number of effects of multiple evaporators, and maximum vapor bleeding in the multiple effect evaporators [1, 11, 37]. On the cogeneration side, recommended energy efficiency measures in cogeneration units include installation of high-efficiency boilers, use of electric drives in place of mechanical drives, use modern and upgraded steam turbines, and drying of bagasse before combustion in boilers [9, 11, 31]. The use of variable speed electric drives will have results in place of steam turbine drives in traditional sugarcane mills. This will release steam used in mechanical drives to efficiently be applied in power generation for surplus electricity. Additionally, variable speed electric drives can better match the varying load of cane crushed and power supply with less wastage [11]. Besides mechanical changes in drives, use of advanced cogeneration technology like the biomass integrated gasification combined cycles (BIG-CC), the biomass integrated gasification with steam-injected gas turbine (BIG-STIG), and biomass integrated gasification with gas turbine (BIG-GT) will further enhance cogeneration potential of the sugar factory [2, 9, 31]. The most common and recommended modification on the steam generation side is the replacement of low-pressure and low-temperature steam boilers with more boilers operating at high steam parameter like temperatures above 450°C and pressures above 45 bar for use in steam turbines for production of excess power. Steam generation efficient can further be enhanced by use of dry bagasse instead of wet bagasse because drier bagasse has got higher heating value which leads to higher boiler efficiency from improved combustion temperature [11].

2.2. Sugar Making Process

2.2.1. Extraction System. Extraction is done to recover as much juice as possible from sugarcane, a process which also produces with specific properties like moisture suitable for burning in the boilers. Juice extraction is done by milling or diffusion both of which require cane preparation by cutting and exposing the cells and fibers using knives and shredders which mechanically driven by either steam turbines or electric motors. Extraction requires large quantities of water to assist in the maximum removal of juice. The main differences between milling and diffusion are as follows:

(i) Sugarcane mills require more mechanical energy than diffusers, i.e., about 15 kW h/tc of cane milled against 10 kW h/tc [54]

(ii) The diffusers demand low-pressure steam for heating juice during the juice extraction. But mills require water in the process called imbibition and subsequent squeezing through a series of mill rollers [1, 54]

(iii) The diffusers have about 99% extraction efficiency compared with milling whose efficiency is limited to 97% [54]

(iv) The moisture content of bagasse from diffusers is higher than that of bagasse from mills making the boiler efficiency lower with diffusers compared to mills [31, 54]

(v) Cane milling allows the production of a higher purity juice, i.e., juice with higher quality of the sugar because of the possibility of extracting juice in the first part of the crushing part [54]

Figure 2 shows the summary of the sugar production process and the flow of various materials and products in a sugar production mill.

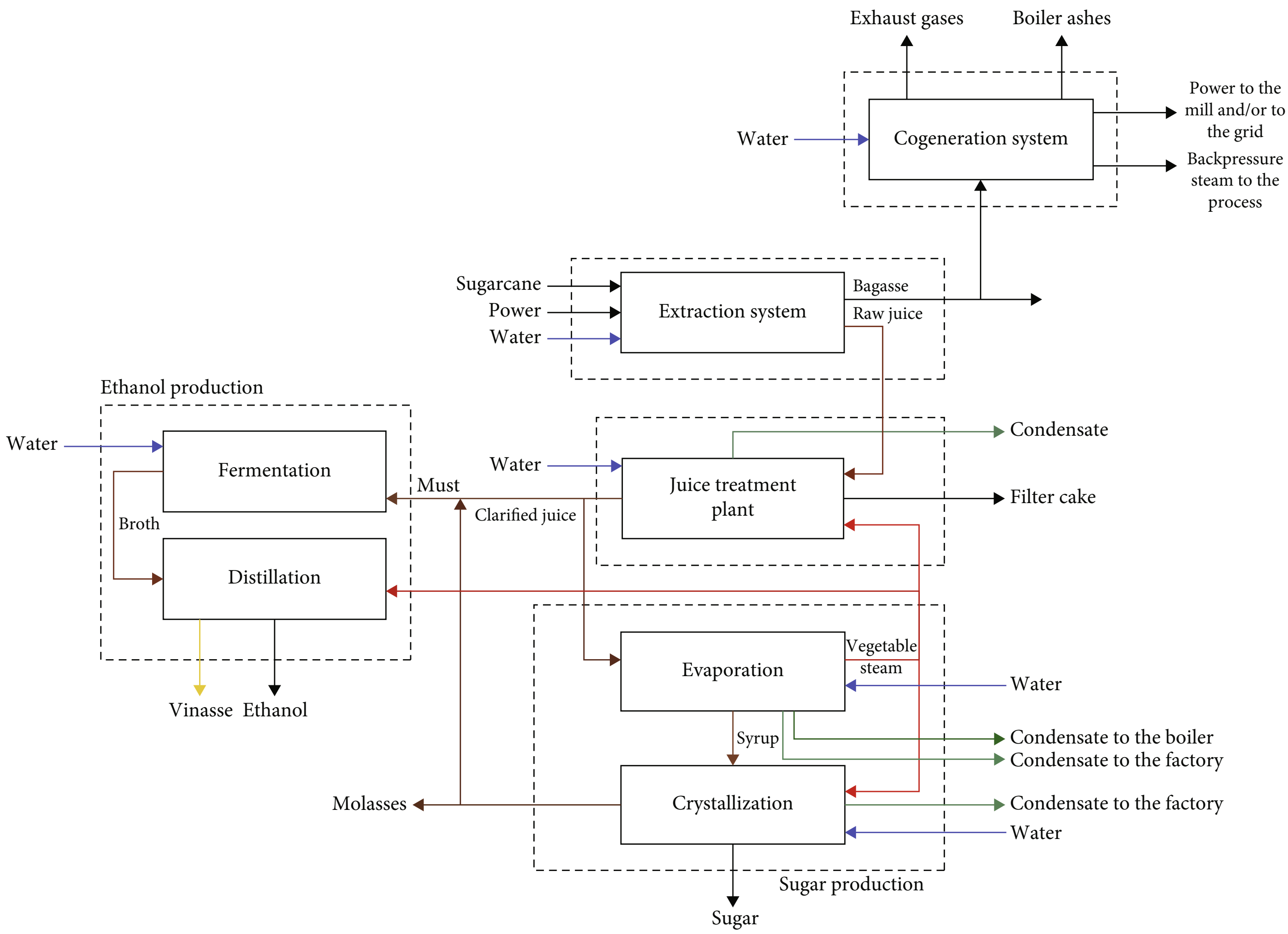

Figure 2: Processes in a sugar factory.

From Figure 2, it is noted that the production of sugar is energy intensive with many processes and equipment applied. These processes are requiring heat in steam, electrical power, and mechanical power for operation. Efficient energy use will ensure the sugar factory as maximum excess power generation and sale to the grid.

2.2.2. Juice Treatment. Juice treatment is done in the process section and involves preparation of the juice by removal of impurities by chemical action to improve the quality of the final products. Raw juice is mixed with filtered juice to form mixed juice and heated until 105°C, by means of vapor from the multiple-effect evaporators. The pH is also adjusted during heating by chemical additions which also agglutinate suspended solids. After the flash tank, the juice is pumped to a decanter for suspended solids to settle at the decanter as mud then sent to filters for clarification before it is pumped to the sugar and ethanol production processes. Part of the juice is recovered in filters from mud while suspended matter with salts formed and fine bagasse are removed as filter cake for disposal or any other applications. Higher thermal integration between the heat exchanger network and the multiple-effect extraction will reduce steam consumption in production process which leads to higher potential for power generation [54].

2.2.3. Sugar Production. Clarified juice is concentrated by evaporation of water in a multiple-effect evaporator to produce syrup, while the vapor called vegetable steam is used for heating purposes in other parts of the process like treatment plant, crystallization, and the distillery. Examples of evaporators used are the Robert-type 5 effect multiple-evaporators and falling-film evaporators. Vapor extractions to other processes are done at the 1st and 2nd effects, although in some cases, vapor from 3rd effect is extorted for use. The use of vapor from the evaporators reduces the demand for steam from the turbine for process applications which avails more steam for power generation.

The highly vicious syrup from the multiple-effect evaporates is taken to the pans for further concentration. This is done under vacuum in pans using vapor from the multiple-effect evaporator for heating. The process in pans creates a mixture of sugar crystal coated in a sugary solution which is transferred to crystallizers from which it is taken to centrifuging sector. The centrifugal force in centrifuges separates sucrose crystals from the sugar solution. The process of centrifuging also involves a stage of washing the crystal with water and steam while it is still in the centrifuge basket. The sugar crystals are taken to the dryers where heating is done to remove moisture using steam. The sugar rich solution from the centrifuges is returned to the cookers for further recovery of the dissolved sugar, until the concentration is reduced in steps. The final solution which is called end syrup or molasses and used in ethanol production or other applications [54].

The sugar making process should be energy efficient in terms of heat or steam consumption by maximum use of vapor from multiple effects, right sizing of motors, use of variable speed drives where possible, and replacement of turbine drives for mill rollers and cane knives with electric drives.

2.3. Conventional and Modern Mills

2.3.1. Conventional/Traditional Mills. Conventional or traditional sugar mills are characterized by low-pressure (20–30 bar) and low-temperature (300–400°C) boilers. They also make use of back pressure turbines (BPT) to provide process steam to various mechanical equipment and generally are not designed to generate surplus power, and hence, they do not supply power to the electricity grid. In some cases, the traditional sugar mills occasionally operate parallel ethanol production facilities as a value-added product from molasses. The traditional mills generally lack electrical power export supply 10–20 kWh electrical or mechanical energy/ton of cane milled while their internal steam demand is 480–550 kg steam/ton of cane milled. The bagasse production by a traditional mill is about 250 to 280 kg of bagasse per ton cane milled. The average moisture content of bagasse has got about 50% moisture content which leads to low conversion efficiency in boilers with low steam parameter leading to underutilization of energy potential of sugarcane feedstock which can be equated to a heat demand of about 2 kg steam/kg bagasse. The challenge facing cogeneration in tradition sugarcane mills is that the cogeneration system is not flexible since bagasse accumulation is almost impossible, as all is consumed during milling. Another challenge facing cogeneration in traditional mills is that sugarcane factories are built as stand-alone plants with no grid connection which limits the ability of the sugar industry to generate surplus power and sell to the public grid Another challenge facing the traditional mill is loss of up to 1/3 of the theoretical cane trash, i.e., tops and leaves by burning cane in the field before harvesting. This is a common practice for areas without mechanized harvesting [11].

The use of low back pressure turbo generators in the traditional mills leads to underutilization of the energy potential of bagasse because the system is inefficient and is designed to dispose of as much bagasse as possible to produce just enough process steam and electricity for the sugar factory. A traditional sugar factory typically produces 250-280 kg bagasse per ton of cane milled to produce 500-600 kg of steam per ton of cane milled which is equivalent to 2 kg steam/kg bagasse produced [12, 55]. According to [56], a sugar mill can generate as high as 320 kg of bagasse per tons of cane processed, but the challenge is the seasonal nature of sugarcane and hence bagasse fuel supply for power generation [56, 57]. Another reason for the underutilization of the energy potential of the sugarcane crop is during cane harvesting; the trash which consist of cane tops and leaves which account for 1/3 total energy in a sugarcane plant is burnt or left in the field [12, 55].

2.3.2. Modern Sugar Mills. Modern sugar factories are characterized by steam generation at high pressure of 45–90 bar and high-temperature boiler installations generally above 450°C. The modern sugar mills are generally equipped with condensing extraction steam turbine (CEST) turbine technology, which can generate surplus power while supplying extracted steam for process applications. To ensure that steam is maximally applied for power generation, modern sugar mills make use of electrical drives in place of steam turbines for mechanical power applications in driving, mills, fans, and other devices in the sugar factory. Diffusers which need less mechanical power are also used in place of mill rollers for juice extraction from sugar [11].

The most common strategy used to generate more electricity for sale to the grid is the transition by the sugar mills to the use of more efficient cogeneration systems consisting of high-pressure and high-temperature steam Rankine cycle cogeneration systems which are currently matured cogeneration systems currently applied in countries like Brazil, India, and Mauritius [54, 58]. By reducing steam consumption in the processes, exergy destruction is reduced the production of sugar and ethanol but with an increase in exergy loss related to a greater amount of excess bagasse used. The net effect is higher exergy-based costs for sugar and ethanol in sugar factories producing ethanol in addition to sugar [58].

Table 1 shows heat-to-power ratios and typical efficiencies for selected methods for cogeneration in the sugarcane industry. Modernization requires the reduction of heat-to-power ratio.

From Table 1, it is noted that the back pressure steam turbine has the lowest electrical efficiency but does not necessary lead to lower overall energy efficiency. However, they have lowest electrical efficiency and heat-to-power ratio and therefore not appropriate where maximum electricity generation is the objective.

It is noted that as the heat-to-power ratio increases, the corresponding electrical efficiency decreases regardless of the higher total energy efficiency (60%-90%). To achieve higher efficiency, there is need to improve the turbine inlet conditions. The traditional mills generally have inlet steam at 20-30 bar and 300-400°C, but more efficient modern cogeneration factories operate with boiler steam inlet pressure of 45-80 bar and 100 bar in some cases and over 450°C steam temperature [12].

2.4. Modernization of Sugar Factories. A retrofit analysis of Indonesian sugar factories showed that the upgraded CEST cogeneration system with same steam parameters used as base case plant, i.e., 30 bar/340°C, but using electric drives could export 45 kWh/TC as excess electricity to the grid while a retrofit using higher steam data of 80 bar and 480°C with electric drives increased exported electricity by 50%. Studies done on a cogeneration power plant of a Brazilian sugar factory that uses a back pressure steam turbine at steam conditions of 22 bar and 300 degrees Celsius had excess generation capacity of 10 kWh/TC as excess electricity for possible export. In another study at Brazilian sugar factory employing back pressure steam turbine (BPST), but

Table 1: Heat-to-power ratios and efficiencies of cogeneration unit.

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

at higher steam parameter of 67 bar and 480°C, it was observed that 60 kWh/TC milled was produced as excess electricity. In a study in an Indian sugar mill applying condensing extraction steam turbine (CEST) technology at high steam parameters of 67 bar and 495°C, it was noted that the sugar mill generated excess power in the range 90–120 kWh/TC. A study in another Indian sugar mills applying CEST technology but at steam parameters of 87 bar and 515°C produced surplus power in the range of 130–140 kWh/TC [11, 59].

The condensing extraction steam turbine (CEST) cogeneration system has the flexibility of producing both electricity and steam for process use during the crop season and electricity alone during the off crop season when process steam is not needed [11].

2.5. Bagasse as a Fuel. Bagasse from sugarcane is a fibrous material that is left after juice extraction at the cane sugar factory that is mainly used as a fuel by sugar factories to generate steam in boilers for process heating and electricity production. Sugarcane bagasse is the fibrous waste that remains after the recovery of sugar juice via crushing and extraction. It also has been the principal fuel used around the world in the sugarcane agroindustry because of its well-known energy properties [15]. The sugar making process normally converts over 25% of the initial weight of sugarcane bagasse. The combustion of bagasse produces about 3–5% of the its weight as sugarcane bagasse ash (SCBA) [3]. Bagasse is rich in moisture whose composition varies between 45 and 55%. In a typical Brazilian scenario, 280 kg of wet bagasse is from a ton of milled cane making it a significant byproduct of a sugarcane factory [3, 15].

Bagasse produced by a traditional factory is in excess of the energy requirement of the factories and often cause a disposal nightmare. For this reason, the traditional sugar mill is design to inefficiently burn off bagasse a waste disposal strategy. It is estimated that use of more efficient bagasse boilers can reduce bagasse consumption by up to 36%, which can be used for more steam and power generation or can be used as feedstock for other processes like bioethanol production [9, 31].

2.5.1. Composition of Dry Bagasse. Sugarcane consists of dissolved solids called brix, water, and fiber. Fiber is an important component of sugarcane that determines the quantity of bagasse produced. Generally, in sugarcane consists of 11 to 16% sucrose content, while bagasse levels range from 27 to 38% [60]. In a typical sugar factory, every 10 tons of sugarcane milled generates about 3 tons of sugarcane bagasse. Bagasse as a fuel has sufficient energy that can be used to supply the entire energy needs of a factory for steam and power generation thus making the industry self-reliant with respect to steam and power needs and export the excess the generation earning extra revenue [61]. According to [62], bagasse is a heterogeneous fibrous residue formed after juice extraction from sugarcane at the mill. Generally, milling 100 tons of sugarcane generates 30–34 tons of bagasse of which 22–24 tons is used to supply energy for sugar production with about 8–10 remaining as excess in a conventional sugar factory. According to [60], 30–32% of the weight of the cane is generated as coproducts. Bagasse consists of 45–55% cellulose, 20–25% hemicellulose, and 18–24% lignin. The composition of dry bagasse is summarized in Table 2.

From Table 2, it is noted that dry bagasse consists of about 28% hemicellulose, 45% cellulose, 1% minerals, 20% lignin, 5% sugar, and 1% ash. The composition of bagasse is similar to wood, but it contains higher moisture content. This makes bagasse ideal for manufacture of paper and pulp, biofuel, filler for building materials, and as a substrate for the growing of mushrooms. The fact that bagasse available is more than what is needed for the energy needs of the sugar factories makes it a candidate for value addition [63].

Sugarcane bagasse has two major types of fibers, rind and the inner pith. Fibers in rind are useful because of their longer length and relatively better mechanical properties compared to fibers from inner pith which have wide applications but have inferior mechanical properties due to short lengths [64]. The stems of cane contain mainly pith (5%), fibers (73%), and the rind (22%) [65, 66]. Pith and the outer rind are sources for fibers in sugarcane. Pith is lighter with a considerably lower density of about 220 kg/m^3 and made up of coarse fibers and large cavities compared to rind whose density is 550 kg/m^3 [60].

2.5.2. Calorific Value of Bagasse. The main application of bagasse is as fuel for steam and power generation for process consumption in juice treatment, fermentation, etc. which requires a minimum of about 50% of the bagasse generated. The excess bagasse is problematic to the conventional sugar factory if it has no alternative application as it leads to safety and health issues like spontaneous combustion and fermentation if stored for a long period of time. It is for this reason that sugar factories deliberately burn excess bagasse mainly by inefficient combustion at the boilers [3, 15].

The calorific value and humidity of biomass are the main determinants of the cogeneration potential of bagasse and other biomass. The average caloric value of dry bagasse is about 18 MJ/kg as compared to other fuels, e.g., bituminous coal has 30.2 MJ/kg, while dry wood is 19.8 MJ/kg [67].

Table 2: Compositing of dry bagasse [63].

	Constituent	Composition (%)
1	Cellulose	45-55
2	Hemicellulose	20-28
3	Lignin	18-24
4	Minerals	1
5	Ash	1
6	Sugar	5
	Total	100

According to [67], the use of bagasse as a fuel can reduce carbon dioxide emissions by about 8% and meet the entire energy demand of the sugar industry.

Bagasse with 50% moisture content has a gross calorific value (GCV) of about 8,816 kJ/kg to 9,600 kJ/kg while the net caloric value is about 7,600 kJ/kg. The gross calorific value of dry ash free bagasse is about 17,632 kJ/kg-19,400 kJ/kg [1, 68]. Sugarcane crop has fiber content of 10-17% by mass which forms bagasse on milling. About 24-30%, i.e., about one quarter of the weight of sugarcane milled, is bagasse [2, 4, 31]. The calorific value of the various bagasse constituents is shown in Table 3.

From Table 3, it is noted that the main components of bagasse are water, fiber, sucrose/sugar, and impurities. However, water is the noncombustible component as the rest, i.e., noncombustible elements of bagasse fuel, while fiber, sucrose/sugar, and some impurities are the combustibles.

The physical properties of bagasse from different sugarcane varieties may vary slightly, but the gross calorific value of dry bagasse is almost constant different varieties and from different countries. Table 4 shows a summary of the gross calorific value of bagasse from different countries.

From Table 4, it is observed that the average (GCV) is 19,488 kJ/kg of dry bagasse. However, since dry bagasse has about 6-7% moisture content, or an average of 6.5%, the give net calorific value of NCV is about 17,850 kJ/kg.

Table 3: Calorific value of different bagasse constituents [1, 68].

Item	Constituent	Calorific value (kJ/kg)
1	Fiber	19,320
2	Sugar	16,611
3	Impurities	17,220
4	Water	0

Table 4: GCV of bagasse by state/country [1, 68].

Country	GCV of dry bagasse (kJ/kg)
Australia	19,076
South Africa	19,257
Hawaii	19,412
Cuba	19,702
Puerto Rica	19,295
Average	19,488

2.6. Sugarcane Trash as Fuel for Cogeneration

2.6.1. Properties of Sugarcane Trash. Sugarcane consists of clean stalk (72%), GSTs (8%), and DSLs (20%) while the amount of trash that remain in the field after harvesting depends on the harvesting method, cane variety, and moisture content (MC) of trash. The moisture content of GSTs and DSLs is about 65% and 15% weight basis, respectively. Since DSLs have about three times more silica than GSTs, the high silica content (2.76%) makes the fodder not recommended for the livestock. The lignin content in GSTs is about 60% higher than DSLs. The high lignin and silica restricts the application of sugarcane trash (ST) for fuel purpose and use as livestock fodder [69]. The sugarcane tops and dry leaves have differences in nutrient content and moisture content. About 80% of N, P, and K is derived from the sugarcane tops hence more nutritive and valuable to the soil leading to use of less mineral fertilizers for sugarcane cultivation. Additionally, the tops have about seven times more moisture than dry leaves and also have higher levels of extractive organic compounds of low molecular weight. It is predicted in studies that dry leaves are more viable for production of second generation ethanol production compared to tops due to better results of yield in the pretreatment steps for dry leaves although glucose yields obtained in the enzymatic hydrolysis step were similar [69, 70].

The chemical composition of sugarcane trash in terms of average percent ash, lignin, cellulose, and hemicellulose is about 7.17 ± 1.65, 20.18 ± 5.75, 44.55 ± 4.70, and 27.44 ± 2.54, respectively. The carbohydrate and silica content in sugarcane trash are about 57.5% and 6.96%, respectively. This shows that trash has potential applications in biochemical conversions like anaerobic digestion for biogas production, biofuel processing, and ethanol production [47]. Therefore, trash has significant potential for power generation, production of 2nd generation ethanol, and production of other biochemical products [70].

2.6.2. Energy Potential of Trash. Sugarcane has emerged as an interesting complementary fuel for the sugarcane factories. Trash is the residue usually left in the sugarcane field in quantities representing about 125 kg trash/ton of cane harvested. Possible pathways in the use of trash for energy purpose conversion to syngas mixed with the bagasse or cofiring with natural gas at the gas turbines can be used in an afterburner to supply extra/additional energy directly to the HRSG [71]. It is however operationally easier to transport straw along with sugarcane in the same truck which increases handling costs [47].

Sugarcane trash has got same energy as bagasse, but it is wasted during open burning at the farms. It is estimated that trash contains one-third of total energy contained in sugarcane. Sugar factories and sugar-producing nations can realize some sustainable and socioeconomic development by harnessing energy in sugarcane trash through creation of extra employment opportunities and conservation of the environment and further contribute to profitability and sustainability of sugar factories. The main limitation is the technological and economic challenges to utilize in commercial exploitation of sugarcane trash for steam and power production. Specific constraints include lack of technological awareness, lack of incentives, poor purchasing power of the farmer, and lack of market for the trash or energy [69, 72].

Besides bagasse as a boiler fuel, trash is a significant material that can be used as boiler fuel. Trash is the residue left in the field after sugarcane is harvested, comprising mainly of leaves and the tops of the plant; cane portions with low or insufficient sucrose content are hence not worthy for juice extraction in milling [73]. On average basis, every ton of sugarcane harvested yields has about 140 kg of trash. However, this only applies in the case of mechanically cane harvesting which involves the trash being blown back onto the field during harvesting as opposed to manual harvesting where the crop is burnt prior to harvesting by workers who chop the stems. This burns leaves, and only leaves the stems and roots as trash. Manual harvesting is a common practice in developing countries including Brazil which had set a targeted 2020 for all harvesting to be mechanical [1, 3, 15].

Dry sugarcane trash contains about 28% of the total energy content in the sugarcane crop. In the study by [73], it was noted that in India alone, if all the cane trash is utilized for energy purpose, the national energy deficit can be cut by 50% and the sugar industry can generate additional 110% power for export. Sugarcane trash contains more silica and alkali making it undesirable as a boiler fuel directly [1, 73]. Therefore, trash processed with the cane supply should be thoroughly washed at mills to reduce the alkali and silica content of resultant bagasse for cases where trash is harvested together with sugarcane and delivered to the factory [73].

2.7. Cogeneration Systems. In the 1970s and 1980s, sugar factories were designed to consume all the bagasse in production of steam and electricity for internal use. The systems were so inefficient that some factories needed additional fuel from elsewhere [1, 74]. In the 1990s and early 2000s, the sugarcane industry faced an open market perspective; hence, there is more need to reduce operating and production costs. Additionally, the economic value of the factory byproducts, i.e., bagasse and molasses, increased while decentralization of generation and the quest for renewable energy sources created a possibility of selling power to the public grids. These development led to a search for more advanced cogeneration systems, using higher steam parameters, while in future, even more advanced systems like biomass integrated gasification combined cycles may be adopted by the sugar mills [37, 58]. These cogeneration systems can attain 35–40% efficiency in power generation. Supercritical steam cycles can also realize such efficiency values, making them attractive alternative to gasification-based systems [74].

The boilers in traditional sugar mills generally operate at steam temperature of 300°C and pressure of 21 bar used to generate electricity using back pressure turbines, with back pressure steam pressure of 2.5 bar for factory thermal applications in processes while the condensate of good quality is fed back to boiler [74]. Modern mills use boilers with higher parameters of 40–120 bar, and produce excess electricity for sale to the using back pressure and condensing-extraction steam turbines [58]. There is much higher generation promise to be generated in future by adopting more efficient configurations like biomass integrated gasification combined cycles (BIGCC), supercritical steam cycles (SuSC), and other advanced gasification-based systems [58, 74].

There are different options for use by sugar factories to simultaneously generate electricity, sugar, and ethanol [58]. The different cogeneration options are as follows.

2.7.1. Conventional Back Pressure Steam Systems (BPST). The back pressure steam turbine (BPST) systems involve the use of a back pressure turbine with exhaust pressure above atmospheric pressure normally 2 to 2.5 bar for process use. These are the most common configuration in many sugar factories. The back pressure system can still generate excess electricity through process modernization to reduce steam consumption as well as steam and power generation efficiency improvement [75].

2.7.2. Condensing-Extraction Steam Systems (CEST). The condensing extraction steam turbine system is applied as an option in which a condensing-extraction turbine is used to supply low-pressure steam extracted from the expansion for process application while the excess is exhausted to the condenser. Other measure to improve performance compared to the back pressure steam turbine is to reduce process steam consumption from average of 500 kg/tc to about 400 kg/tc [9, 75]. Both BPST and CEST can use different steam generation temperatures and pressures, e.g., 42 bar/400°C, 42 bar/450°C, 67 bar/480°C, 67 bar/515 C, 80 bar/520°C, 100 bar/520°C, and 120 bar/540°C [75].

2.7.3. Supercritical Steam Systems (SuSC). The supercritical steam system is an improvement of the condensing extraction steam system. The system used very high steam parameters and regenerative heat exchangers for preheating boiler feed water which effectively improves the cycle efficiency. There is also a possibility of applying gas turbine for power generation; thus, a biomass gasification-based system is a possible option. Bagasse and cane trash are dried and sent to a gasifier, to produce producer gas which is used as a fuel in the gas turbine system while turbine exhaust gases are passed through a heat recovery steam generator (HRSG) to generate steam for use in a condensing-extraction turbine for extra power generation [1, 74].

2.7.4. Biomass Integrated Gasification Combined Cycles (BIGCC). There are two main configurations for BIGCC technology. They are low-pressure air-blown and high-pressure air-blown [74, 75]. The BIGCC is made up of four major subsystems, namely, fuel system for handling and feeding fuel to the BIGCC system, the gasifier, the gas clean-up unit (GCU), and combined cycle system. The gas turbine system and steam turbine system are integrated together [58, 74].

2.8. Cogeneration Potential of Sugar Factories. Cogeneration in sugar factories involves simultaneous production of thermal energy and electricity with bagasse as a fuel. With cogeneration, the total efficiency of the sugar factory increases to about 50% [44, 76]. The traditional factories generate just enough electricity and steam for factory internal use while high efficiency cogeneration sugar mills have boilers with high thermal efficiency, more efficient condensing extraction steam turbines, or other efficient turbines to produce excess electricity and have modernized process equipment and drive systems that consume less steam and electricity to maximize the power production and export [77, 78].

Bagasse cogeneration is the use of the fibrous sugarcane waste called bagasse to produce electricity and heat by sugar factories [1, 2, 57]. The energy potential of bagasse is determined mainly by the moisture content and the energy generation technology applied in power generation and steam generation. The electric power output is fundamentally dependent on market rules and incentives available like feed in tariffs and other drivers of production efficiency [2, 57].

Bagasse fiber accounts for 25 to 30% of the weight sugarcane milled factory with 50% being the moisture content [1, 26]. The thermodynamic performance of a bagasse cogeneration facility can be expressed in the form of energy utilization factor, heat-to-electricity ratio, fuel saving ratio exegetic efficiency, and electricity produced per ton of cane. Cogeneration plants using high-pressure, Rankine cycle steam turbine generally produce 115–120 kWh/tc, while BIG-GT and BIG-STIG have very high generation potential of 270–275 kWh/tc. Cogeneration with the back pressure and condensing steam turbines have energy and exegetic efficiencies of about 22–25% and 60–70%, respectively. Other important parameters for the sugar factory and bagasse cogeneration power plant are the steam consumption which varies between 480 and 550 kg/tc milled. The electricity demand of a sugar factory varies between 16–22 kWh/tc for mill turbine driven mills and 32–40 kWh/tc for electrified mill drives [2, 9].

The conventional sugar mills with no power export generally produce 10-20 kWh electrical energy/tc and consume 480-550 kg steam/tc, while modern mills applying efficient conversion systems produce electrical energy in the range of 115-120 kWh/tc. Application of steam saving measures in the sugar factory releases steam from process and milling application to production of extra power. From various studies on bagasse cogeneration, it was established that reducing steam consumption from 500 by 30% to 350 kg/tc increases power generation by 24% while partial use of cane of cane trash can increase excess power generation by or twofold [1, 12, 31].

There are many benefits that come with investment in export cogeneration by sugar factories as a diversification strategy. They include revenue diversification, stabilization of the sugar industry, job creation, and extra revenue and stable revenue for sugarcane farmers [79]. Cogeneration experience from countries like India, Réunion, Mauritius, Brazil, and Cuba has proved that the sugar industry can supply significant electricity to the grid which helps in mitigating the greenhouse emissions and help countries realize their emissions and climate targets [3, 69].

Sugar production is an energy intensive undertaking which requires energy mainly in the form of heat/steam and electricity. In the conventional or traditional factory, a back pressure turbine supplies electricity and steam from its exhaust for process use. The modern sugar mills generally use the condensing extraction (CEST) which is more efficient to generate electricity in excess for internal use and sale to the grid while extracted/bled off steam is used for process thermal applications. The main sugar factory energy-consuming equipment are the cane knives, cane carrier elevators, the gantry cranes at cane yards, the mill drives, conveyers, pumps, evaporators, pans, centrifuges, and mills having either electric drives of steam turbine drives [68, 79]. The mills and cane knives are driven by either steam turbines or electric motors although electric motors are considered to be more energy efficient [80].

The efficiency of conventional cogeneration systems using back pressure turbines has about 25% at steam pressures of 20-30 bars. For systems using pressure of 45-66 bars, the electricity potential is about 100 kWh per ton of milled. For high-pressure boilers of average of 82 bars, the generation capacity is about 110-130 kWh per ton of cane crushed based on experience from Reunion, Mauritius, India, and Brazil. There are basic bagasse cogeneration configurations applied, namely, intermittent generation in which the power generation is based on sugar production needs, continuous cogeneration power plants that are designed to operate continuously during the sugarcane crop season with bagasse as main fuel, and the firm power plants which operate throughout the year except for planned maintenance. Firm power normally operates for 300 days and are stopped for 65 to 66 for routine maintenance [80]. The characteristics of the three types of bagasse cogeneration power plants are shown in Table 5.

From Table 5, it is noted that firm power plants have the highest generation capacity and use boilers with highest steam pressure of 82 operate at high load factors of 90% followed by the continuous power plants which also operate at a load factor of about 90% bars and use boilers with medium pressure range of 30 to 45 bars. The intermittent power plants usually use low-pressure boilers of pressure 25 to 30 bars which are associated with the traditional sugar factory conditions.

The internal electricity consumption is limited to 30% for the continuous and firm power plants while the intermittent power plants generally consume 25 kWh/ton of cane milled. The steam-to-bagasse ratio is 2.5 for the continuous and firm power plants hence more efficient than the intermittent whose ratio is 1.8 : 2.2 on average basis. Another indicator of steam efficiency is the steam consumption which is 400 kg/ton of cane for continuous and firm power plants and 500-600 kg/ton for the intermittent mills.

The average turbine capacity for an intermittent power plant is 0.5 to 3 MWe for intermittent power plants, 15 MWe for continuous, and 30 MWe for the firm power plants. However, we have several cases of capacities beyond the stipulated range [1, 18, 19].

2.9. Investment Costs for Bagasse Cogeneration. The investment cost for bagasse cogeneration power plants depends on the net export capacity and technology adopted. Low-

Table 5: Comparison of the three cogeneration setups that can be adopted by sugar mills.

	Parameter	Intermittent generation	Continuous generation	Firm power generation
1	Power generation capacity (kWh/ton)	10	60	110-130
2	Cane milling rate	10 TCH or 240 TCD	150 TCH or 3,600 TCD	230 TCH or 5600 TCD
3	Load factor and availability	Intermittence allowed	Continuous at 90% load factor	Continuous at 90% load factor, 300 milling days or 7200 hours a year, and 65-66 days for maintenance
4	Ratio of steam to bagasse	1.8 : 2.2	2.5	2.5
5	Steam pressure (bars)	25 to 30	30-45	82
6	Type of turbine used	Back pressure	Condensing	Condensing type
7	Boiler capacity (tons/h)	40	120	140-150
8	Steam consumption	500-600 kg/ton of cane crushed	400 kg/ton of cane milled	400 kg/ton of cane milled
9	Electricity consumption	25 kWh/ton of cane crushed	30% internal consumption	Not more than 30% internal consumption
10	Turbine capacity	0.5-3 MWe	At least 15 MW	At least 30 MW

pressure plants cost about $1.4 million/MW, and midrange pressure systems cost about $1.8 million/MW while the high pressure at the top end costs about to $3.1 million/MW. These costs compare favorable against heavy fuel plants which cost about $1.1 million/MW, geothermal at $2.25 million/MW, and $2.5 million/MW for hydroelectric power plants. The advantage of bagasse power plants over the thermal power plants is that they do not have a fuel cost assuming bagasse is waste product or byproduct of sugar production process, but the thermal power plants have significant fuel costs that are passed directly to consumers in addition to the electricity or energy costs [81].

2.10. Investment Options for Bagasse Cogeneration. Experience from past bagasse cogeneration projects provides general investigation guidelines for bagasse cogeneration plants for a 5,000 TCD sugar factory for corresponding steam pressures of 45, 60, and 82 bars. Table 6 is the summary of the various parameters of the cogeneration plants.

From Table 6, it is noted that, based on factory size and choice of technology, there are three types of boilers that can be selected for generation of steam based on a 5,000 TCD sugar factory. The steam pressure ranges from 45 to 82 bars or closer denominations. The annual electricity revenue is between USD 4 and USD 8.3 million dollars, and payback period ranges between 4.5 years and 8.8 years based on experience from similar projects.

3. Performance Analysis of Nzoia Sugar Factory

The data for this study targeted operations at Nzoia Sugar Company's sugar factory which is based in Western Kenya. Documents were analyzed to gather data on current and historical performance of the factory. The data collection instruments used were questionnaires, interviews, and observation.

3.1. Steam Boilers. The boiler parameters for the factory are summarized in Table 7.

From Table 7, it is observed that the factory has 3 boilers with capacity 108 tons/h with average age of over 39 years consuming about 54 tons of bagasse per hour and thermal efficiency of about 60% which lower than current modern boiler efficiency. Under steady milling conditions, the factory consumes about 76.9% of bagasse produced creating a buildup of 24.1% as excess bagasse production. The old boilers also have means high operation and maintenance cost and low thermal efficiency. Poor steam generation has a huge implication on milling throughput and overall production [2].

3.2. Steam and Electricity Generation Capacity. The factory is equipped with the three boilers and steam turbines for steam and power generation. The average steam and power generation by the factories are summarized in Table 8.

From Table 8, the average availability of the factory is about 275 days out of 365 days or a year hence 76% availability while the average milling capacity 46 TCH/125 TCH which is just a capacity factor of 37%. The average electricity load for the factory is 2.8 MW against the unit capacity of 3 and 4, respectively; hence, a total installed capacity of operating turbines is 7 MW. This implies that the power plant load factor is 0.4 or 40%.

The cane processing statistics can be used to generate bagasse energy production and use. The traditional systems are characterized by generally low efficiency that is typical of many sugar factories in operation globally. Modern sugar mills generate surplus electric power to export to the grid [15, 82]. Bagasse accounts for about 30% of the weight of sugarcane milled, for the case of burnt cane which is characterized by limited trash. According to [15, 82], a traditional sugar mill produces 25 kWh or 90 MJ per ton of milled sugarcane. Total steam consumed in milling, and heat is about 910 MJ/ton of cane milled. Bagasse consumption is generally split into 10% for electric power and 90% for other uses.

3.3. Turbines. Nzoia Sugar Factory is equipped with steam turbines used for power generation in the power house and as prime movers for the mills and cane knife. The factory

Table 6: Investment guidelines for bagasse cogeneration projects [1].

Component	Possible plant options		
Boiler pressure (bar)	45	60	82
Recommended plant capacity (tons of cane per day)	5000	5000	5000
Boiler capacity (tons of steam per hour)	140	140	140
Bagasse feed rate (tons per hour)	58	62	70
Turbine capacity (MW)	25	30	50
Daily power generation, gross (MWh)	420	550	820
Equivalent capacity (MW)	18	24	40
Daily export power, net (MWh)	260	330	550
Equivalent export capacity (MW)	12.5	14	24
Total capital investment ($ million)	18	25	75
Estimated local component ($ million)	4	5	12
Estimated annual revenue from electricity ($ million)	4	5	8.3
Simple payback period (years)	4.5	5	8.8

Table 7: Current condition of power generation in NSC [32].

Parameter	Rate/value
Daily bagasse production	1040 tons
Usage (bagasse)	800 tons
Current availability of bagasse	Available
Daily cane availability	Available
1 watertube fixed grate boiler 25 bar 330°C	54 tons/h
2 FCB water tube boiler 23 bar 320°C	27 tons/h each
Number of boilers	3
Average age of the boilers	39 years old
Efficiency of the boiler	60%
Optimum capacity operating capacity	3 MW
Domestic consumption	2.8 MW
Export to the grid	0
Steam pressure range	20-25 bars
Current operation of the plant	Operational

has got 3 turbo generators for electricity generation whose exhaust is used as process steam for heating. The specifications of the turbines are shown in Table 9.

From Table 9, it is noted that Nzoia Sugar Factory has got three turbo generators with one written off. They operate as back pressure steam turbines exhausting steam at design pressure of 1.5 bars which is ideal for process heating applications. The average design turbine inlet steam pressure is 23.7 bars. Therefore, the sugar factory has installed capacity of 7 MW.

3.4. Factory Performance Analysis. The performance of a sugar factory is measured in terms of parameters like cane milled, sugar produced from cane milled, availability of bagasse fuel which relies on through put in milling, cost of production, and profits made [4, 80]. The performance of the factory was analyzed from the available factory production and generation data. They include records on sugarcane deliveries and data on juice production on daily, weekly, monthly, and annual bases. Sugar and molasses production data was also accessed to analyze the overall production and operations of the factory.

3.4.1. Cane and Sugar Production. The rate of milling which determines availability of bagasse fuel for the boilers is a function of the state of the factory, cane availability, and delivery to the factory for milling.

The study collected data for sugar production, cane milled, and the TC/TS ratio for the periods 2009 to 2017. The statistics are summarized in Table 10.

From Table 10, it is noted that the average annual sugar production is 662,068.22 tons and average cane milled per year was 684,070.78 while the TC/TS ratio was 11.02. The ratio of cane crushed to sugar made TC/TS is high implying inefficient conversion. With the factory design capacity of 3000 TCD, maximum possible cane milling per year representing 365 days is 1,095,000 tons of cane. This represents a capacity utilization of 62.47%.

The revenue and hence sustainability of a conventional sugar factory mainly depend on the quantity of sugar produced. Therefore, a great deal of effort is needed to ensure maximum extraction and production of sugar from sugarcane crop. Some sugar is usually lost in bagasse, the filter mud/cake, and the molasses. Careful process control and use of efficient equipment are needed to minimize these losses [83].

The efficiency of a sugar factory is measured by the rendement. It is defined as the sugar produced expressed as a percentage by weight of amount of cane milled. Rendement is mathematically expressed as a product of sucrose content of sugarcane, juice extraction efficiency, and process house or boiling house sugar recovery efficiency. The typical figures are

$$\begin{aligned}\text{Rendement} &= \text{percentage of sucrose in cane} \\ &\quad \times \text{juice extraction efficiency} \\ &\quad \times \text{boiling house sugar recovery efficiency} \\ &= 12\% \times 0.93 \times 0.9 = 10.04\%. \end{aligned} \tag{1}$$

Table 8: Operational conditions: quantity and units.

	Operational conditions	Quantity	Units
1	Average cane milled/year	402,741	TC
2	Cane milling/h	46	TCH
3	Average bagasse production	13.8	t/h
4	Steam capacity	108	t/h
5	Average steam pressure	22	Bar (g)
6	Average steam temperature	300	°C
7	Direct steam supply to process at pressure-reducing valve	10-15	t/h
8	Average electricity demand for the factory	2.8	MW
9	Annual factory availability (effective working days)	275	Days

Table 9: Turbine technical data.

	Parameter	Dresser-Rand	Kessel (multistage)	FCB turbine not operational	Average
1	Output (MW)	3	4	0	3.5
2	Normal speed (rpm)	5400	6480	—	—
3	Trip speed (rpm)	5400-5300	6480-6000	—	
4	Steam pressure (bars)	23	25	23	23.7
5	Steam temperature (°C)	300-330	300-360	300-330	330
6	Exhaust pressure (bars)	1.5	1.5	1.5	1.5

Table 10: Table of sugar produced and cane crushed over years at Nzoia Sugar Company [20].

Year	Sugar produced (TS) (tons)	Cane milled (TC) (tons)	TC/TS
2009	68254	679,568	9.96
2010	65859	645591	9.81
2011	61886	652170	10.5
2012	64669	690996	10.7
2013	55535	680364	12.3
2014	49648	596186	12
2015	86821	924721	10.7
2016	59218	706173	11.9
2017	46724	580868	12.45
Total	558,614	6,156,637	—
Average	62,068.22	684,071	11.02

Therefore, overall recovery efficiency is the product of juice extraction and the boiling house recovery. In some cases, the inverse of rendement is used to represent the efficiency. Some sugar industries use the inverse of tons of sugar to tones of cane crushed or TC/TS [83]. In this case, the above example will yield a TC/TS ratio of 9.96.

Maximum sugar cane yield or production is achieved if cane with high sucrose content is used and crushed efficiently in mills while the process house efficient should also be high.

3.4.2. Sugar Conversion Efficiency. The sugar conversion efficiency is the ratio of sugar made to sugarcane milled. It is a measure of the conversion efficiency of a sugar factory. The TC/TC ratio for the periods 2009 to 2017 is presented in Figure 3.

Figure 3 shows that the TC/TS ratio which is the sugar conversion efficiency or relationship between tons of cane milled and tons of sugar made is not constant and generally proportional to the milling throughput.

The performance of the factory as shown in Figure 3 shows that the factory realized the lowest TS/TC in the year 2010, an indicator of better extraction, and the highest value was realized in the year 2017, which is an indicator of poor juice and sugar recovery and corresponds to the year with the lowest throughput and hence lowest production over the period under review. The graph shows significant drop in sugar processing in 2010 where only an outrun of 9.81 was realized. A significant rise in sugar outrun was experienced in 2013 with the scenario repeating itself in the year 2017 which happens to have witnessed lowest sugar production. The graph generally shows fluctuations in sugar outrun over years. High TC/TS ratio is an indicator of poor sugarcane to sugar conversion efficient which is a characteristic of poor cane loading in mills or intermitted milling which leads to poor juice extraction from sugarcane during milling [1, 84].

With average TC/TS ratio of 11.02, it can be concluded that the sugar factory has poor conversion efficiency which should be improved [21].

3.4.3. Steam and Power Consumption. Sugar factories are designed for self-sufficiency in electricity production with sugar production as the core function. A well designed and operated sugar factory with medium pressure steam configuration of 15-25 bars is self-sufficient in steam and electricity

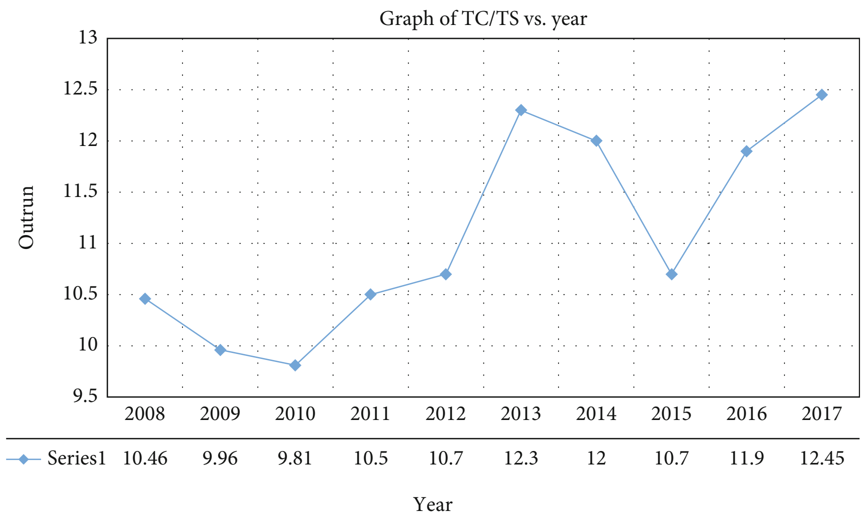

Figure 3: Graph of sugar outrun over years at Nzoia.

production to meet factory demand [85]. This study established the energy and production of the sugar factory from current and historical records. The study showed that average specific steam consumption (ssc) is 675 kg steam/ton of cane milled while electricity consumption is 28 kilowatt hour (kWh) per ton of cane milled (kWh/tc). The electricity generation on average is 24 kWh/tc which implies that the factory does not have self-sufficiency in electricity and relies on grid power to meet its deficit [85, 86]. Therefore, the factory should establish self-sufficiency in electricity generation and export excess to the grid through design and operation measures to reduce demand and increase generation.

4. Results and Discussion

A sugar mill is a multipurpose factory that can produce energy, food, energy, and biofuels simultaneously from the same product. Factors that enable cogeneration by the sugar factories are availability of investment capital, attractive feed-in tariffs, and availability of boiler fuel throughout the year which is limited by intermittence in milling of cane and inefficient energy generation and use [87].

The performance analysis of the factory had average factory utilization of 62.47% for the period between 2009 and 2017 which implies that 37.53% of production resource capacity is not utilized. Makeup water or fresh water consumption accounts for 34.73% which implies that recirculation of condensate is at the rate of 65.27% against an ideal case of 100% condensate recovery and recirculation. There is a need to reduce steam leakages and losses for maximum recirculation to reduce water consumption and related water treatment. With about 8.4% of the steam loss in boiler blowdown and cleaning of boiler tubes during the process, improvements to reduce steam consumption are to improve water treatment and use compressed air instead of steam for cleaning boiler tubes.

The analysis of records further showed that the factory records an average bagasse percent cane of 37.87%. The average bagasse moisture content is about 50.5% which is slightly about recommended range of 48%-50% for optimum combustion and steam generation [31, 37]. The average boiler efficiency is 54.4%, a performance that can be improved by the use of dry bagasse whose calorific value is higher than that of wet bagasse used [1, 2, 9, 86].

The current global fossil fuel-dominated energy systems are unsustainable at a time the entire world is committed to reduction in energy-related emissions and the global climate change. Sugarcane is one of the several renewable energy options, for over 100 sugar-producing countries. Sugarcane is one of the most productive species in conversion of solar energy to chemical potential energy in biomass. The main challenge with energy from sugarcane is that the supply and hence power generation are limited to the crop harvest season for many countries [53]. The sugar industry faces sustainability challenges like declining sugar prices, more competitive land uses, and governance issues in some countries. However, immense opportunity remains to harness electricity from the industry and supplement revenues as well as supply of green electricity [1, 53]. Despite the significant potential of power generation from the sugar factories, several economic, environmental, technical, and social challenges hinder the development of bagasse power generation. Other challenges are unreliable and hence fluctuating cane supply for milling and legal and investment-related issues like corruption and lack of governance transparency, which compromises the sustainability of the entire sugar industry.

It is technically and economically feasible to integrate advanced electricity generation systems into sugarcane factories for generation of electricity for internal and sale of excess to the electricity grid [12]. This however requires modernization of the traditional sugar factory to increase energy efficiency and maximize on electric power generation [1, 2, 12]. The traditional mills using mechanical steam turbine drives for mills and other equipment like cane knives and fans have higher steam consumption since the drives are less efficient and thus limit electricity generation potential of the sugar mills [9, 12, 31].

This study showed that the factory whose daily milling capacity is 3000 TCD is underutilized due to many operational and technical challenges like plant break downs, shortage of cane supply for continuous milling, and low conversion efficiency of cane to sugar hence reduced sugar output per cane milled. The overall effect is that the average milling capacity for the period underutilization is about 2500 TCD corresponding to 83.3% capacity utilization.

Cogeneration is an entrenched practice by the sugar industry with almost all sugar factories producing own electricity, and in some cases, sugar factories sell excess electricity to the grid earning extra revenue while contributing to the energy transition through supply or renewable energy to substitute fossil fuel sources [13]. These require policy, legal, and technical measures to facilitate export cogeneration. The analysis of the factory power plant shows severe underutilization of the cogeneration capacity, hence lost opportunity in terms of jobs, revenue, and green power for the grid. The main factor limiting cogeneration is use of the traditional low-pressure boilers and back pressure steam turbines for power generation instead of modern efficient high-pressure boiler extraction steam turbines. To maximize power generation and efficiency, steam consumption in process activities should be minimized and made efficient. The steam turbine prime movers for the cane knives and three mill turbines should be replaced with efficient maximum export of power to the grid requiring that the sugar factory adopts energy conservation measures for reduction of internal energy consumption of both steam and electricity [14]. The plant availability is 75.0% which shows that the bagasse cogeneration plant is idle and unproductive electric motors so that all steam is directed to an efficient extraction-condensing turbo generator which supplies process steam through extraction of expanding steam from the turbine.

The key to increased bagasse electricity production by the sugar industry is to use boilers and steam turbines with higher pressure and steam configuration. Two key technical innovations within cogeneration plants have emerged. The use of multiple fuel in firm power plants has also played a key role in enhancing electricity production by sugar factories. For example, modern bagasse/coal cogeneration plants in Mauritius generally operate at 81 bars and up to 87 bars in India. Much higher pressure of up to 115 bars can also be used, although it requires higher investment capital and more stringent water treatment and process control technologies which further increase the cost of investment as well as operation and maintenance [1].

The main challenge with use of coal in bagasse cogeneration power plants is higher greenhouse gas emissions and coal ash which is about 14% of the coal mass which introduces the challenge of competition for land use landfill facilities. Additionally, coal ash power plants may contain between 15 and 30% unburnt carbon [61]. A carbon burnout facility can be used to generate low-pressure steam for use by the sugar factory and in the process reduce the unburnt carbon content to below 6% [62]. The resultant processed ash can be used in the construction industry as feedstock for cement/concrete production [61]. Therefore, bagasse cogeneration power using coal as substitute fuels can add value to the building industry besides the direct role in supplying heat and electricity for the sugar factories.

Facilitating policies ought to be put in place to encourage the generation and use of clean energy in manufacturing industries. The policies should be incorporated into national regulatory framework to realize multiple maximum benefit investment and to provide a conducive investment environment. Cogeneration by the sugarcane manufacturing industry is well-established technology currently employed by all sugar factories [50]. However, export-based cogeneration to the grid is not a global practice [1, 2, 31]. For bagasse to be considered intensively, a regulatory framework strengthens existing legal and juridical frameworks to promote the export of power by sugar factories to public utilities [67].

Overall, assessment shows that bagasse cogeneration has significant potential, but pertinent issues need to be resolved. Among challenges is access to finance, the feed-in tariff structure, ability and willingness of the grid to absorb intermitted power supply due to relatively low availability and factory utilization by the sugar factory and unreliable sugarcane supply to the grid as demonstrated by the collapse of Mumias Sugar Company whose intermittent and unreliable supply to the grid led to accumulation of huge penalties from the electricity utility company as breach of supply terms specified in the power purchase agreement. This experience from Mumias will definitely reduce the interest in bagasse cogeneration unless policy measures are put in place to protect the sugar factories against punitive tariff regime from utility companies in terms of uptake of intermittent power [1, 31, 50].

There are a number of differences between the traditional mill and the modern sugar mill. The traditional mills have higher steam consumption to many factors like inefficient steam turbine drives and less efficient steam generation and conversion systems [11]. Traditional or conventional sugar mills have higher steam consumption compared to modern sugar factories. The use of steam turbine mechanical drives by traditional mills is inefficient and consumes steam that can be efficiently used in more efficient turbine generation systems to yield more for internal use by electric drives and have excess for export [11]. The conventional electric motor drives can also be substituted with variable speed drives in operations where they are cost effective and more efficient like the cane carrier and bagasse carrier elevators, whose feed rate is not always constant [1, 2].

4.1. Technical Capacity. Nzoia Sugar Factory has got very old boilers averaging 39 years at the time of the study which well beyond the acceptable age of boilers which is 10 to 20 years. The same applies for the steam turbines which besides being old are of the inefficient back pressure and low steam parameter type. These factors combined with low cane availability and overall availability of the factory significantly limit the bagasse cogeneration capacity of the traditional sugar factory. Therefore, the old turbines and boilers should be replaced with new and more efficient boilers and steam turbines [20].

4.1.1. Boilers for Sugar Factories. If the boilers operate at maximum and continuous rating, the output would be 170 t/h of steam. The current steam generation is about 108 t/h of steam on average which is about 60.24% of the design capacity. The boilers are designed to operate at a superheat temperature and pressure of 330°C and 65 bar. The boiler feed water is preheated in economizers to 126°C. The computed average boiler efficiency is 64.03%. This efficiency is significantly lower than the standard efficiency of modern billers which is 70-80% which leads to low steam generation capacity. The study showed that the average age of boilers at the sugar factory was 39 years against recommended age of 10 to 20 years. The use of old and inefficient boilers contributes significantly to low thermal efficiency of the sugar factory [9, 18, 80].

The factory has poor steam efficiency averaging 580 tons per ton of sugarcane milled or 58% of cane milled which implies wasteful use of bagasse energy resources. Efficient sugar factories have average steam consumption of about 40% cane milled in addition to efficient steam to electricity conversion systems with less internal or process use hence excess generation to support export of power to the electricity grid [11, 88]. More boiler fuel feedstock can be by collection and transport, of cane trash and tops from the field to the sugar factory for use in steam and power generation in higher steam pressure and temperature [1] although this implies more costs in transport and handling of extra biomass but will lead to more steam and power generation [13, 88].

Steam boilers facilitate the operation of crystallization and drying in sugar mills by generation and supply of process steam and steam to run turbines for power generation. Boilers with traveling grates are preferred for like coal and biomass and bagasse for easy in supply of combustion air and ash removal hence reduction of combustion air requirements and design capacity. Too much air increases efficiency and increases carry over which causes equipment erosion for economizer and induced draft (ID) fans as well as ducts [89].

Generally, a conventional sugar factory requires about 500 kg of low-pressure process steam per ton of came milled. Additionally, for a traditional mill, steam turbines are often used as prime movers for mills and cane crushers and cane knives, which increases steam requirements beyond 500 tons/ton of cane milled [61]. Therefore, investing in modern condensing-extraction turbines will increase the generation capacity and efficiency of the traditional sugar factory.

4.1.2. Steam Turbines for Sugar Mills. There are two types of steam turbines in use, i.e., the back pressure turbine and the extraction-condensing turbine [61]. The choice on the best choice between back pressure turbine and extraction-condensing turbine is guided by factors like quantities of process steam and electricity required, available steam quality, and economic considerations like cost. For extraction type turbine, steam can be extracted at more than one point based on the temperature and pressure requirements for process applications [72]. The extraction system can be the single extraction options or multiple controlled also called pass-out and uncontrolled or bleeding type extraction system [61].

A single-stage back pressure impulse-type steam turbine has efficiency of about 25 to 30% while the condensing steam turbine or multistage steam turbines can achieve efficiency of 80% to 89%, which maximizes power generation. The low pressure for process use is extracted at an appropriate stage and pressure from the condensing type turbine [61].

4.1.3. Overall Efficiency. The study showed a high sugarcane/sugar ratio ranging from 9.8 to about 12.5 and average of 11 which is an indicator of poor sugar extraction efficiency across the processes. This ratio should be reduced by increasing efficiencies from milling, i.e., juice extraction and process sugar recovery in crystallizers and centrifuges. A recommended ratio is one ton of sugar from 6 tons of cane crushed as the target in line with best practices in global sugar manufacturing practices by investing in efficient sugar conversion technologies and equipment [90]. The overall sugar factory efficiency is also low as represented by a capacity utilization of about 64.47% [34].

There are different cogeneration technology and equipment options for investors, whose choice is a function of factors like availability of investment capital, the feed in tariffs, cost of alternative sources of electricity, the type of electricity substituted, and policy and legal framework that may also influence choice in terms of size and type of technology. The government should put in place financial and nonmonetary measures to encourage investment in the bagasse cogeneration [1, 2, 9, 75, 91].

4.2. Electricity Potential of the Factory. This study showed that there is wasteful use of bagasse energy resources at the conventional sugar factory hence the need to optimize energy generation and by development of a more energy efficient sugar factory power plant producing excess power for export to the grid while meeting own internal energy needs. The electricity generation capacity with frequent milling interruptions makes the factory an importer of energy especially electricity instead of being an exporter to the grid.

Although the design capacity of the turbo generators is 4 MW for Kessel and 3 MW for the Dresser-Rand (DR) turbine, average electricity load of the sugar factory is 2.8 MW, hence a capacity factor of 0.4. This implies that 60% of the generation capacity remains unutilized by the factory. The existing design is a traditional one that seeks to achieve maximum bagasse consumption and disposal, minimize electricity generation and combustion, and maximize steam consumption for process applications which is against the objective of a modern sugar factory whose objective is maximize electricity generation and minimize process steam consumption.

A performance analysis of the conventional sugar factory showed that it has a high ratio of TC/TS (tons of cane crushed/tons of sugar made) and a high bagasse pol (sugar content of bagasse) which are indicators of poor extraction at the sugarcane mills and poor process house sugar recovery from juice. High bagasse pol causes undesirable effects to bagasse combustion like formation of clinkers on furnace grates which inhibits boiler performance and efficiency by restricting the flow of undergrate combustion air. High bagasse moisture content also negatively affects the combustion and steam rate by reducing the heating value of bagasse fuel. Good milling practice produces bagasse with moisture content of 45 to 50%, yet the average moisture content for the factory targeted in this study is 52% [1, 72]. Therefore, there is need to modernize the over 40-year-old mills (mills were installed in 1978) and ensure proper mill settings and throughput which are factors that affect the moisture content of bagasse. Drying bagasse is another option, but economic feasibility should be investigated under prevailing factory production set up.

The factory boiler FCB boilers (boilers 1 and 2) were installed in 1978 and are therefore older than 44 years while the Dresser-Rand (DR boiler 3) is over 30 years; hence, average boiler age is about 40 years against recommended life span of 10-20 years or average of 15 years. The study recommends retirement of the old and obsolete boilers with modern efficient boilers of high-pressure and high-temperature configuration or medium temperature and pressure configuration based on desired type and capacity of desired modern bagasse power plant for the factory [9, 37]. Another strategy to reduce factory steam demand is to convert the steam turbine drives for the sugar came mills to electric motor driven drives to use the steam used by the three team turbine electricity generations.

There are three basic cogeneration configurations which are normally based on plant design and capacity. These configurations are the intermittent power plants which generate electricity only when milling sugarcane and hence during the crop season only. Therefore, power generation is based on the production needs and hence is not continuous. The continuous bagasse power plants are designed to operate continuously, but the operations are still linked to sugar production during the crop season. The electricity potential is realized in firm power plants which use high-pressure steam and condensing extraction turbines operating for an average of 300 days per year with the remaining period being used for planned maintenance. Firm power plants are delinked from the sugar factory operations other than the bagasse fuel received which is often complimented by an alternative fuel like coal or gas during the out of crop season when the sugar mills are not operational [2, 9, 31].

The average milling capacity of the sugar factory for the period under consideration was 580,868 tons of cane per year to 924, 721 tons of cane per year. From guidelines presented in Table 5, a continuous power plant of electricity capacity of 60 kWh per ton of cane milled is recommended upon improvement in the factory energy efficiency in reduction in steam and power consumption. Recommended steam pressure configuration is preferably 30 bars to 40 bars and steam production capacity of about 120 tons/h. Conversion of the steam turbine drives for the mills and cane knife will reduce steam demand and increase electricity generation for the motors and excess for export to the grid. Overall internal steam consumption by process operations should be reduced to below 30% of total steam generation, replace the back pressure steam turbine with more efficient condensing extraction turbine (CEST), and increase the factory viability and milling throughput for steady bagasse supply to boilers for steam [4, 9, 18].

Electric power from bagasse cogeneration can be applied to complement use of grid connected fossil fuel sources like gas turbines, coal, and diesel engine power plants and help mitigate the negative impact from seasonal hydroelectric power and variable renewables like wind and solar while simultaneously generating alternative revenue sources for the highly competitive sugar industry. Electric power from bagasse is cleaner compared to fossil fuels and nuclear power. The farmer payment regime in most countries is such that farmers are paid for the weight of cane based on sugar content. This has placed financial pressure on both farmers and millers with small pieces of land and millers struggling to sell their sugar in a highly subsidized and competitive sugar market. Through bagasse cogeneration, it is possible to pay farmers and millers extra revenue from the electricity sold to the grid making fiber an economic constituent of the sugarcane for extra revenue [14].

Bagasse cogeneration is of immense economic value since most sugar-producing countries are less developed with high levels of unemployment and low access to grid electricity. Bagasse cogeneration if successfully adopted will accelerate social and economic development for the sugarcane-producing nations. Agricultural activities account for about 45% of the sub-Saharan Africa economy. The agroindustries need various forms of energy for production and operations and the employees where over 313 MW of installed generation capacity is installed in five sub-Saharan countries of Kenya, Malawi, Uganda, Tanzania, and Ethiopia power capacity in agroindustries with over 270 MW coming from bagasse cogeneration [50].

4.3. Socioeconomic Benefits of Bagasse Cogeneration. Bagasse cogeneration has got several socioeconomic and technical benefits which include the following:

(i) Leads to lower carbon dioxide emissions from fossil fuel sources of power generation through substitution of fossil fuel sources with renewable sources

(ii) Leads to economic viability of sugar factories from extra revenue through sell of near-zero fuel cost electricity

(iii) Will lead to more diverse, secure, reliable, and widespread grid electricity supply

(iv) Reduction in the transmission and distribution (T&D) costs, through decentralized generation in sugar-producing areas

(v) More social benefits through employment creation for local populations

(vi) Many sugarcane-producing countries heavily rely on fossil fuel sources like coal for electricity generation. Bagasse cogeneration for heat and power production will reduce energy-related greenhouse gas emissions

(vii) Since many of the sugar-producing countries have high energy import bills for fossil fuels, energy from local resources will save on foreign currency and improve their balance of payment position [1, 2, 57]

Therefore, the investment in clean energy by the agricultural sector improves energy access, reduces cost of energy, improves energy security, and promotes power grid stability. Other benefits are improved economic performance of plant job creation, new business and cash inflow opportunities, reduced emissions and pollution, poverty alleviation, better well-being, higher productivity, higher capabilities and better skills, and enhanced innovation [50]. With high and reliable availability of bagasse at the point of generation use, readily available and fully matured energy conversion technologies, and cost competitiveness compared with other energy resources, bagasse cogeneration can be a key player in the global and national energy transition measures.

Sugarcane bagasse (SCB) can be used as a feedstock for biofuel production due to its high biomass content and yield, ease of harvesting, collection, and storage. Bagasse can be used in biofuel production via the biochemical route which is an eco-friendly option. In some countries like Brazil, the sugar industry is traditionally used in power and ethanol industry to meet own energy needs in processes and export the electricity for sale on the national grid. There are hard choices to make between increasing electricity generation and increasing ethanol production by biochemical processing of bagasse or pursue both cases. This is both a technical and a commercial challenge.

4.4. Energy Potential of Sugarcane Trash. Sugarcane trash can be recovered by means of a sugarcane harvester and trash collecting mechanism, shredders, bailers, and shredders and collected for delivery to the factory by chopping and transporting together with sugarcane billets without drying also the integral harvesting or balling the trash in field after harvesting and transporting separately. Handling and handling transportation costs remain the main limiting factor in the use of trash as an energy resource. About 70 to 80% of sugarcane trash can be harvested, and the remaining 20 to 30% is left in the field [72].

4.5. Recommendations. The study showed that a conventional sugar factory like that at Nzoia Sugar Company Ltd. has many opportunities to improve energy efficiency and profitability thorough export cogeneration. There is wasteful use of energy resources, both electricity, steam by the traditional sugar mill that should be optimized through modernization of plant and equipment. Modernization will maximize steam generation, reduce internal energy consumption, and increase to power ratio to steam consumption ratio which will avail significant amount of electricity for export to the grid as opposed to a traditional sugar factory which is designed maximize bagasse consumption through combustion in inefficient steam boilers as a disposal method while generating just enough steam and electricity to sustain the sugar factory operations.

Cogeneration by the sugar mills can be improved by measures like increasing biomass supply by including sugarcane tops and leaves or trash as well as the development of new varieties of sugarcane which have higher biomass potential besides high sucrose content [1, 31]. Optimum power generation by the sugar industry will be achieved by stablishing an enabling state-of-the-art firm power plants for sugar factories with emphasis on energy efficiency to minimize energy consumption and maximize generation and export of electricity [52]. Since many sugarcane producers worldwide face economic and general sustainability challenges, sugarcane bagasse cogeneration can boost the sugar industry by providing an extra, stable revenue stream which will enhance the competitive position of sugar manufacturing factories. For Brazil and other ethanol-producing countries from the sugar industry as a petroleum substitute, enhanced sugar factory efficiency will reduce the cost of ethanol which would accelerate the rate of fossil fuel substitution as international oil prices remain high.

Key recommended measures to support bagasse cogeneration are as follows:

(i) There is need to develop a clear the planning and regulatory paths for enhanced development of bagasse cogeneration infrastructure. They include fair and easy access to the public grid for both large and small sugar factories

(ii) Use of financial and tax incentives, to hasten initial development of cogeneration facilities in sugar mills which makes it easy and cheaper for investors to buy and install necessary cogeneration equipment and infrastructure and hence boost the electricity output while at the same time make the most effective onsite use of heat and electricity generated. The common and effective financial incentives include attractive renewable energy feed-in tariffs

(iii) There is need to investigate into more efficient and alternative conversion technologies which promise to yield more from the sugarcane biomass [4, 57]

(iv) Minimize bagasse moisture content to improve the heating value by modernizing the mills (current mills were installed in 1978 hence are old and obsolete) and improve on mill settings and milling throughput which are the main factors affecting bagasse moisture content

As demonstrated in Table 10, the factory has a high TC/TS ratio which implies that the overall sugar extraction process from cane milled is low. The bagasse pol which is a measure of amount of sugar in bagasse is higher than recommended losses. These have two challenges, i.e., low extraction of sucrose at the mills, while high sugar in bagasse causes clinkers on the boiler furnace grades which inhibit under grate air supply which leads to poor combustion and reduced efficiency in steam generation [1, 2]. The factors that influence the choice of bagasse cogeneration technology and equipment include energy prices, type of electricity substituted by cogeneration, policy and legal framework, available monetary and nonmonetary incentives, total investment costs, and conversion efficiency technological choice.

This study showed that the average age of the boilers is 40 years against the recommended life cycle of 10 to 20 years or average of 15 years. Likewise, the average age of the turbines is over 30 years against recommended age of 5 to 15 years or an average of about 10 years. This is evidence that the company is using old and obsolete boilers and turbines making cogeneration inefficient, wasteful, and expensive. Additionally, the use of inefficient back pressure steam turbines and generation of steam at low pressure and steam configuration makes further reduces cogeneration potential of this conventional power plant, hence the need to write off and replace the old conversion equipment [18, 31]. As a traditional factory, the primary cane knife is driven by inefficient steam turbine instead of electric drive systems unlike the secondary knife which is electric motor driven, likewise the three cane sugar mills which are driven by three mill turbines as opposed to the use of diffusers in modern sugar mills or mills driven by electric drives as opposed to use of inefficient steam turbines. The factory should reduce the steam demand by converting the turbine drives to electric drives for the cane knives and mills. This will release the steam used for power generation. Factory electricity consumption can be reduced by replacing constant drive motor with variable speed drives and right sizing of motors to increase motor efficiency and reduce electricity consumption [4, 9]. This will avail more electricity for export to earn revenue for the factory.

The study showed that the average moisture content bagasse leaving the last mill to the boilers is about 52%. This is significantly higher than what can technically be achievable which is 45-48%. This implies that the boiler efficiency and hence steam production capacity are reduced as a result of high moisture content which reduces the heating value of bagasse fuel. It is therefore important to reduce bagasse moisture content by ensuring optimum milling throughput and correct mill setting to reduce moisture content which will improve steam generation and juice extraction simultaneously [37, 38, 80].

The conventional sugar factories which use inefficient conversion systems like boilers and steam turbines save just about 10% of bagasse produced. This is an indicator of significant bagasse fuel wastage.

The new boiler has higher efficiencies on both bagasse and coal which suggests that fuel consumption is much lower as compared to the current boilers. The steam capacity of the new boiler would rather be retained to avoid extra cost in purchasing and relaying of steam pipes and turbine. However, a final design decision should provide the best measures for maximum generation capacity utilization. A conversion to a firm power plant with coal as an alternative fuel is expected to improve the availability of the plant from the current level of 75% to about 90% throughout the year with provision for routine maintenance and other factors. With such high availability ratios, reliability in power production is expected to rise among the consumer. Efficiency of the boiler is much higher on coal as compared to bagasse; this is because coal has less moisture content than bagasse. Moisture content of bagasse stands at 52% which is higher than recommended. At this level, efficiency of the boiler is reduced. Modern methods of bagasse drying will improve this situation.

Steam turbines of 50 MW are in operation in the modern sugar factories while small mills generally use turbines of electricity capacity of 6 MW. Large sugar factories can also use turbines of electricity capacity of 45 MW which are in the market [61]. In a typical case on April 30, 2016, the largest turbine manufactured in Brazil for the sugar and ethanol industry was commissioned at Usina Delta with capacity of 73.4 MW operated by steam at 520°C and 67 bars [61]. This demonstrates the advances in steam turbine technology for the sugar industry [60, 64].

Studies have demonstrated the significant energy potential of sugar trash that can be exploited. The main challenge of using cane trash for energy generation is that it plays an important role of soil fertility replenishment at firm level where it is allowed to decompose in sugarcane farms. Due to the huge energy potential of cane trash, there is a need to investigate the feasibility of harvesting trash with sugarcane for delivery to the factory for use as an energy resource for heat and power generation. Of particular concern is the handling costs involved and effect on the sugar production processes and quality. The parallel option of harvesting, balling, and delivery to the factory for power generation also needs further studies on its feasibility and overall impact to the sugarcane and energy sector.

Governments should put in place policy measures through attractive electricity feed in tariffs, other tariff, and nontariff measures to encourage investment in cogeneration by the sugar factory while avoiding the bitter lessons from failed cogeneration witnessed at Mumias Sugar Company Ltd. whose operations collapsed cogeneration activities because of overreliance on bagasse as the only fuel for the power generation and punitive measures from the power utility company for loss of generation resulting from unavailability of sugarcane and the factory for bagasse production and supply to the cogeneration plant [31, 38]. Therefore, successful export cogeneration for a traditional sugar factory requires technical modifications in the factory design and operations, enabling policy and legal measures by the government and the electric utility company. Other important measures are access to competitive capital for investment in technology, plant, and equipment for modernization.

5. Conclusion

The traditional or conventional sugar factory is an example of an industry where energy is intensively used and at the same time wasted. There is great need for more efficient use of energy resources to maximize overall energy efficiency of sugar mills help reduce global greenhouse gas emissions from the energy sector. Overall energy efficiency in sugar factories can significantly be increased by maximizing electricity generation and minimizing power and factory steam consumption to have enough power for export by generating using more efficient condensing extraction steam turbines. Modernization requires technical, financial, and policy measures by investors, governments, and electricity utility companies. Technical measures to enhance cogeneration capacity include improvement power-to-heat ratio to acceptable range for a modern sugar factory which is 0.3 to 0.5 as opposed to 0.04–0.07 for the traditional mill by reducing internal use of thermal energy. Modifications recommended are change from steam turbine drives to variable electric drives and replacement of steam turbines and electric motors, shift from the higher capacity back pressure turbine to condensing steam turbine, use of high-pressure and high-temperature boilers, drying of bagasse, or reduction in the average moisture content. Other than technical measures, modernization requires significant financial investment and facilitating policy and legal measures like enabling power purchase agreement to buy excess power sustainably.

Sugar mills generate bagasse whose energy potential is more than the entire energy needs of a traditional sugar factory hence the common practice of deliberately using inefficient energy systems for steam and power as a means of excess bagasse disposal nightmare. The use of more efficient bagasse boilers can reduce bagasse consumption by up to 36% which can be used to generate more steam and electricity for export to the grid. It is necessary to diversify sugarcane factory business portfolio to compete against low cost dumped in the market. Through export cogeneration, additional revenue streams will be availed to the struggling industry.

This study concludes that for traditional sugar factory of capacity 3000 TCD, the electricity generation potential is about 15 MW based on the continuous cogeneration power plant technology. However, for the potential to be exploited, the factory should improve on its availability and throughput to ensure steady milling and power generation. The factory availability should improve to about 90%. This can be achieved by minimizing factory breakdowns and minimum interruptions in cane supply for continuous milling as well as reduced steam consumption by the factory through measures like electrification of steam turbine drives and use of condensing extraction steam turbines instead of back pressure turbines and increased steam generation by efficiency by the boilers.

Abbreviations

BIGCC: Biomass integrated gasification combined cycles
BIG-STIG: Biomass integrated gasification with steam-injected gas turbine
CEST: Condensing extraction steam turbine
FCB: Five Cail Babcock of France
GWhrs: Gigawatt hours
kW: Kilowatt
MW: Megawatt
SCBA: Sugarcane bagasse ash
ST: Sugarcane trash
SuSC: Supercritical steam systems
TC: Tons of cane
TCD: Tons of cane crushed per day
TCH: Tons of cane per hour
TS: Tons of sugar.

Data Availability

The authors will provide any data used upon written request.

Additional Points

Highlights. (i) Diversification by the sugar industry will increase the socioeconomic value of the sugarcane crop and enhance the sustainability and profitability of sugar factories. (ii) Bagasse cogeneration is of immense economic value since most sugar-producing countries are less developed with high levels of unemployment and low access to grid electricity. (iii) Bagasse cogeneration if successfully adopted will accelerate social and economic development for the sugarcane-producing nations. (iv) A conventional sugar factory has a high energy to electricity ratio which should be reduced by modernization to maximize electricity generation and export to the grid. (v) Cogeneration by the 3000 TCD factory studies can generate an average of 15 MW electricity for own use and export of the excess based on average factory performance statistics. This will be more if the factory is modernized and operated at design capacity.

Consent

The authors have freedom and authority to publish the manuscript for public use.

Conflicts of Interest

The authors declare that there is no conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancies have been completely observed by the authors.

Authors' Contributions

The first author drafted the manuscript which was reviewed and improved by the second author.

Acknowledgments

As authors, we thank Michael Vermeer who edited our work and gave it the current shape. The whole exercise was fully funded by the researchers.

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