SSRG International Journal of Electrical and Electronics Engineering
ISSN: 2348-8379/ https://doi.org/10.14445/23488379/IJEEE-V11I8P109

Volume 11 Issue 8, 91-111, August 2024

Review Article

Empowering Sustainability: An Insightful Review of Sugar Cogeneration Contributions to Electrical Power Systems

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Received: 04 June 2024 Revised: 07 July 2024 Accepted: 04 August 2024 Published: 31 August 2024

Abstract *- Sugar cogeneration, which uses bagasse to create power and heat, promises to improve energy efficiency, reduce emissions, and increase sugar mill profitability. This abstract focuses on three main methods: Boiler Combined Heat and Power (CHP) and Steam Turbine Techniques. CHP systems play an essential role in producing power and heat simultaneously, whereas boilers convert bagasse into steam for power generation. High-pressure boilers and current designs incorporate advanced combustion technology and heat recovery systems to improve efficiency and performance. Steam turbines incorporate modern technologies to transform high-pressure steam into energy efficiently. Sugar mills save energy by utilizing bagasse-derived steam. These cogeneration technologies offer a sustainable energy option for the sugar sector, increasing economic competitiveness and environmental sustainability by lowering fossil fuel consumption and emissions. Additional research and innovation are required to improve efficiency and fully utilize this renewable energy source.*

Keywords *- Sugar industry, Combined Heat and Power (CHP), Steam turbines, Boilers, Sugar cogeneration.*

1. Introduction

Sugar co-generation is the simultaneous production of sugar and power by sugar mills or refineries [1]. It is a sustainable and effective energy production technique that generates electricity from sugar manufacturing by-products [2]. Typically, this technique includes burning bagasse, a fibrous by-product from sugarcane processing, to generate steam [3]. This steam then powers turbines connected to generators, which generate energy. Sugar co-generation is exciting because it encourages resource efficiency and waste reduction [4].

Traditionally considered a waste product, Bagasse is now a sustainable fuel source, reducing the dependency on fossil fuels for energy generation [5]. Furthermore, sugar co-generation facilities frequently generate extra electricity that can be sent to the grid, which is increasing. overall energy supply [6]. The combination of co-generation plants and sugar mills improves the economic feasibility of sugar production by diversifying revenue streams [7]. Sugar mills can sell extra electricity to utilities, creating additional revenue. Furthermore, co-generation facilities can boost the overall energy efficiency of sugar production, making it more sustainable and environmentally benign [8]. Sugar cogeneration is a sustainable and economically effective method of energy production in the sugar industry. Sugar co-generation plants benefit the sugar production process and the overall energy landscape by generating electricity from bagasse, improving resource efficiency, and lowering environmental impact [9]. When sugar co-generation is combined with electricity systems, it provides various benefits. Sugar co-generation is a renewable energy source that decreases reliance on fossil fuels by burning bagasse as a fuel [10]. This decreases the danger of variations in fossil fuel costs and supply disruptions, improving the stability and security of the electricity grid. It also supports environmental sustainability by lowering greenhouse gas emissions and mitigating waste and disposal impacts [11].

Sugar co-generation further improves the efficiency of sugar-producing facilities by converting heat from bagasse combustion into steam, which powers turbines to generate energy [12]. This integration maximizes energy efficiency and resource utilization, resulting in cost savings and better operational performance. Sugar co-generation also helps to promote rural development and economic progress by providing major employment opportunities in sugarcane-growing areas [6]. The additional cash earned by selling surplus electricity to the grid can boost local economies and fund community development efforts. Co-generation facilities may also allow technology transfer, skill development, and infrastructure investment, thereby promoting socioeconomic growth in the region [13]. Sugar co-generation provides numerous benefits, aligning with energy and environmental goals as the globe shifts to cleaner, more sustainable energy sources [14]. There are some limitations to using sugar co-generation in power systems. Sugar co-generation is a renewable energy source dependent on the sugarcane harvesting season, resulting in intermittency and impacting system stability [15].

The principal fuel is the material, a by-product of sugarcane production. that is only available during these seasons, potentially causing power supply interruptions. The initial capital expenditure for cogeneration plants can be significant, and integrating systems with existing sugar mills or refineries necessitates retrofitting and adjustments [2]. Despite being considered a greener alternative to fossil fuels, sugar co-generation emits pollutants during combustion, contributing to air pollution and greenhouse gas emissions [16]. Furthermore, co-generation plants may demand water for steam generation, thus affecting water resources in areas with restricted water supply [17]. Limited flexibility and efficiency pose additional obstacles, necessitating careful planning, technological investment, and policy support [18]. Sugar co-generation maximizes power generation by burning bagasse in boilers to produce steam, which is then utilized to power turbines attached to generators [19]. This system, commonly known as CHP, generates power and useable temperature from a single fuel source while utilizing waste heat for heating [20]. High-pressure boiler systems achieve maximum efficiency by working at high pressures and temperatures [21]. Combined Cycle Power Plant (CCPP) combines gas turbines and steam turbines to increase efficiency. Advanced control and monitoring systems are critical to improving plant performance and reducing downtime [22].

Renewable energy integration can help complement electricity output when bagasse is limited. Research gaps prevent sugar cogeneration technologies from being optimally integrated and utilized in electrical power systems despite the industry's notable accomplishments in this field and their benefits to renewable energy portfolios. Creating more economical and efficient techniques for turning biomass into energy, improving grid integration techniques to control intermittent power outputs, and reducing the environmental effects of processing sugarcane by-products are important areas that require additional research. Furthermore, few thorough studies address sugar cogeneration's scalability and long-term sustainability, especially under different economic and climatic circumstances. To fully realize the potential of sugar cogeneration to deliver a more robust and renewable source of energy system, these gaps need to be closed. The major difficulty is fine-tuning sugar cogeneration systems to minimize emissions while maximizing energy efficiency and profitability. More investigation and creativity are required to maximize the effectiveness and realize the full potential of bagasse as a renewable energy source.

1.1. Cogeneration Techniques in the Sugarcane Industry

Cogeneration, commonly known as (CHP), has enormous potential for increasing energy efficiency in sugarcane processing plants. This section examines the implementation of cogeneration systems in sugarcane mills; processing is used as the primary fuel source. Various cogeneration topologies, including the Gas Turbine Combined Cycle (GTCC) and the Organic Ranking Cycle (ORC), are evaluated for suitability and performance in the sugarcane industry.

1.1.1. Benefits of Cogeneration

The simultaneous generation of heat and electricity from a single fuel source is referred to as CHP. It incorporates several ideas and technologies, with surplus electricity being fed back into the public grid to save energy or exported to the grid for more cash. Diesel power plants that use cogeneration use various equipment, such as engines, electric generators, Rankin cycle steam turbines, heat recovery units, and system control devices. The main drivers are steam turbines, which offer a range of applications and performance choices. Compared to conventional thermal systems, cogeneration systems exhibit an efficiency of over 80%, while Combined Cycle Power Plant (CCPP) systems can realize an efficiency of up to 55%. Reduced energy costs and greenhouse gas emissions associated with generation are the advantages.

1.2. Boiler Technique of Sugarcane Processing

Sugarcane processing relies heavily on boilers to generate steam for juice extraction, evaporation, and crystallization operations. This section delves into sophisticated boiler technologies designed for the sugarcane sector, such as Ultra-Supercritical (USC) and Fluidized Bed Combustion (FBC) boilers. The emphasis is on improving steam-generating efficiency while reducing environmental emissions and resource use.

1.2.1. Benefits of Boiler Technique of Sugarcane Processing

Pressure boilers are critical to the sugar industry's energy efficiency and productivity. By efficiently burning bagasse, a fibrous byproduct of sugar cane production, they reduce their dependency on fossil fuels and other non-renewable energy sources. This decreases running costs and improves sustainability. Pressure boilers also contribute to cogeneration by producing high-pressure steam from bagasse combustion, which powers turbines attached to generators, supplying electricity for various sugar mill operations. This excess power can be exported to the grid, generating additional revenue. Steam is also employed in various industrial processes to optimize energy use and improve operational efficiency. Pressure boilers increase environmental sustainability by reducing greenhouse gas emissions.

Advances in boiler technology have increased combustion efficiency and emissions, elevating the ecological credentials of pressure boilers in the sugar sector.

1.3. Steam Turbine Technique for Power Generation

Sugarcane mills use steam turbines to create energy by converting steam from boilers. This section assesses the suitability and performance of various steam turbine topologies in the sugarcane sector, such as backpressure and multistage turbines.

1.3.1. Benefits of Steam Turbine Technique for Power Generation

Steam turbines are critical in sugarcane because of their efficiency, adaptability, and environmental benefits. They transform heat energy into mechanical energy, which is then transferred into electrical power, thus improving energy efficiency, lowering operating costs, and enhancing profitability. These turbines are adaptable and reliable, adjusting to changing steam conditions and loads. Sugarcane mills produce bagasse, a fibrous residue that can be used as a renewable fuel to generate steam in boilers, contributing to the industry's sustainability and lowering greenhouse gas emissions.

2. Survey of the Sugarcane Industry in Power System

2.1. Cogeneration Techniques in the Sugarcane Industry

Cogeneration, also known as CHP, is a sugarcane industry that uses bagasse residue to generate electricity and heat for sugar production and distillation, providing economic advantages for the environment, like increased sustainability and energy efficiency. In the sugarcane industry, cogeneration uses bagasse the fibrous residue left over after sugar is extracted from the plant to produce heat and power simultaneously. The sugar industry has long used bagasse as boiler fuel to generate steam for grinding processes. Modern cogeneration methods have developed to provide a cost-effective and sustainable energy solution by addressing the mill's internal energy requirements and supplying excess electricity to the grid. Key technologies include high-efficiency boilers, CHP systems, and sophisticated steam turbines. These systems take advantage of the energy content of bagasse to create high-pressure steam that powers turbines to produce electricity and heats the mill's processes. This dual-generation capacity lowers emissions, reduces the need for fossil fuels, improves the energy efficiency of sugar mills, and advances the sustainability and general profitability of the sugar sector.

Bhutani, R. et al. [23]: Cogeneration is a technique used in the sugar industry to turn process heat and steam into energy. The capacity to generate electricity is increased using advanced cogeneration systems, such as BIG-CC systems and high-pressure direct combustion SRC networks. The main topics of this article are the use of bagasse and other sugarcane leftovers, together with BIG-CC systems, in India's sugar industry. The cogeneration's overall power output and efficiency increase with temperature and pressure. Nevertheless, unique building methods and materials that can tolerate high pressure and temperatures (over 450°C) are needed for high-pressure systems.

Rey, J. R. C. et al. [24]: The application of BIG-GT technology to the sugarcane sector to produce heat and power using bagasse as a fuel is the subject of this study. Then, the four configurations were analyzed, and a sensitivity analysis was performed. The results revealed that BIG-GT boosted power generation efficiency by 14.3% while requiring additional bagasse acquisition. Bagasse gasification produced thermal energy in configuration IV, increasing electricity-generating efficiency by 5.9%.

Chantasiriwan, S. et al. [25]: The study examines a backwards-feed multiple-effect evaporator's energy efficiency in a cogeneration system used in a sugar factory. When it comes to evaporating sugar juice, the backward-feed multiple-effect evaporator uses less energy than the forward-feed multiple-effect evaporator. Both evaporators process the same amount of sugar juice, have the same total heating surface area, and operate at maximum efficiency. More efficient is the backward-feed multiple-effect evaporator.

Ankit, R. K. et al. [26]: The energy and analysis of a cogenerative sugar mill boiler are the main subjects of the study. The boiler is a self-powered system that consists of a boiler, a turbine, and sugarcane juice heating tanks. The energy balance analysis determines the boiler's energy destruction or irreversibility rate. After examining the boiler's first and second law efficiencies, it determined that its energy and exergy efficiency were 68.99% and 26.10% under the specified atmospheric conditions.

Kumar, U et al. [27]: The study aims to demonstrate bagasse gasification's potential as a strategy for reducing greenhouse gas emissions by simulating the sugar mill and bagasse gasification process with ASPEN Plus® software. The gasification process can boost the electrical energy produced by combusting bagasse from 0.57 kWh/kg to 1.16 kWh/kg with 10% moisture. The study intends to encourage cleaner and more efficient energy use in industrial waste, emphasizing the role of biomass energy in reducing greenhouse gas emissions.

Upakool, J et al. [28]: This study looks at biomass-based cogeneration power plants in Thailand to improve energy efficiency and lower CO_2 emissions. A survey of ten sugarcane processing plants identified monitoring requirements for these facilities. Optimal practices were examined in a field case study of a 25 MW plant in Nakhon Sawan province. In order to lower local air pollution and CO_2

emissions, the research highlights the necessity of policies that encourage and control the construction of cogeneration power plants. Dhavane, N. C et al. [29]: This study attempts to use poultry litter as a fuel substitute in a sugar mill cogeneration power plant, as unregulated litter disposal damages fields and contributes to greenhouse gas emissions. Collecting approximately 100 tonnes of manure daily may create electricity in the power plant, making this a viable solution for the sugar factory's cogeneration plant. This method may significantly reduce the environmental impact of poultry litter disposal in India.

Kabeyi, M. et al. [30]: The study examined the efficiency of the 120 MW Kipevu III power plant and the feasibility of a cogeneration facility using an exhaust gas boiler and an RCST. The results showed that a Rankin cycle cogeneration facility could create an additional 10 MW of electricity, representing an 8.4% increase. This would boost power output and revenue, reduce environmental effects, and lower power prices by lowering particular fuel generation and profits from fuel energy expended. The techniques, advantages, limitations and results of Cogeneration techniques in the sugarcane industry are shown in Table 1.

Table 1. Cogeneration techniques in the sugarcane industry

Ref. No.	Author Name	Techniques	Advantages	Limitations	Results
25	Bhutani, R. (2020)	This research focuses on applying the BIG-CC system in the Indian sugar industry, specifically bagasse and other sugarcane byproducts for energy conversion.	Comparing the BIG-CC system to the standard steam turbine and lower pressure boiler systems in sugar plants reveals several advantages.	The BIG-CC technique, which includes complicated processes such as biomass gasification, syngas purification, and burning in a combination of the cycle power plant, necessitates advanced technical knowledge and training.	The total output power of a cogenerate system is 1,886.14 kW at 10 bar pressure and 100°C temperature.
26	Rey, J.R.C. (2021)	In order to produce thermal energy and power from bagasse as a fuel, this study examines the use of Integrated Biomass Direct Gasification/Gas Turbine (BIG-GT) technology in the sugarcane business.	The BIG-GT system generates electricity more efficiently than the CEST system. Biomass gasification turns solid fuels into gaseous fuels with improved characteristics; however, a gas-cleaning system is required before being used in a GT, despite its advantages over the CEST system.	BIG-GT systems require a significant initial investment due to complicated equipment and infrastructure, resulting in more substantial capital costs than typical co-generation systems.	The BIG-GT system improved power and generation efficiency by 14.3% over conventional systems, with gains of 9.1%, 11.0%, and 12.6% in various configurations.
27	Chantasiriwan, S. (2020)	The energy efficiency of a forward-feed evaporator and a backward-feed multiple-effect evaporator is compared in this study.	Backwards-feed evaporators have higher energy efficiency than forward-feed evaporators. The opposing direction movement of steam and liquid allows for better heat energy utilization and lower energy usage.	Backward-feed evaporators may have a more significant initial capital cost because of their complicated design and construction.	In comparison to a cogeneration system that uses the forward-feed multiple-effect, one that uses the backward-feed multiple-effect is more energy-efficient, as it produces more power for the same fuel.

28	Ankit, R. K (2020)	This project aims to analyze a boiler's energy in a co-generative sugar factory.	Cogeneration systems combine electricity and heat generation, using heat to produce sugar, resulting in higher energy efficiency than separate systems that squander heat.	Implementing a cogeneration system, including boiler equipment, can be expensive, potentially discouraging adoption by smaller or less financially secure sugar plants.	The plant's energy efficiency is 68.99% and 26.10% under the first and second thermodynamic principles, respectively, with an energy destruction rate of 84.96 MW.
29	Kumar, U (2021)	The ASPEN Plus® program models the complete sugar mill and bagasse gasification process, allowing the study to investigate the possibility of increased efficiency.	Bagasse, the fibrous leftover from sugarcane processing, can be gasified to produce valuable gases such as hydrogen, carbon monoxide, and methane, allowing energy to be recovered from this biomass resource for use in various applications.	Gasification processes are complex and need engineering and chemistry expertise, which may increase initial investment costs and operational issues.	Combusting bagasse generates around 0.57 kWh of electricity per kg. The gasification process can generate Bagasse with 10% moisture content (by weight) and produce up to 1.16 kWh/kg.
30	Upakool, J (2021)	This study identifies metrics for monitoring Cogeneration plants to increase energy efficiency and reduce CO_2 emissions.	Establishing metrics enables continual evaluation of a cogeneration plant's Performance regarding energy efficiency and CO_2 reduction. This aids in identifying areas for enhancement and optimizing operations.	Implementing appropriate metrics can be difficult, requiring comprehensive data collection, analysis, and interpretation, raising the cost and resource needs for monitoring energy efficiency and reducing emissions.	The case study analysis demonstrates that the metrics used to monitor and operate cogeneration power plants may also be used to evaluate energy efficiency and CO_2 emission reductions.
31	Dhavane, N. C (2020)	This project aims to use accessible poultry litter as a substitute fuel for a cogeneration power plant in the sugar industry.	Using poultry litter as a fuel source decreases dependency on traditional fossil fuels, lowering greenhouse gas emissions and helping to ensure environmental sustainability.	Due to its high nitrogen and phosphorus content, poultry litter can contaminate air and water if not managed properly. Pollutants, including sulphur dioxide and nitrogen oxides, are released when litter burns and particulate matter, which may impact local air quality.	Poultry litter production from poultry farms is 0.094 kg/day, and 3 MW power generation requires 138.61 tonnes of litter fuel. This necessitates 14.74 lakh chicken chickens near the area, lowering gasoline transportation expenses. Cogeneration utilizing chicken litter during the 180-day off-season can generate power at a low fuel cost.
32	Kabeyi, M (2022)	A cogeneration facility that used an exhaust gas boiler	Cogeneration plants often have higher overall efficiency	Cogeneration systems are more modern than typical power plants. However,	A study on a 120 MW Kipevu III power plant found

		and a Rankin cycle steam turbine to convert waste heat was examined, as well as the performance of the 120 MW Kipevu III power plant.	than standalone power plants because they use remaining heat that would otherwise be squandered.	adding a steam turbine and an exhaust gas boiler increases maintenance requirements, raises operational costs, and may reduce reliability.	that a collective 119.7 MW Kipevu III diesel engine power plant could generate 10 MW of additional electric power, increasing power output and revenue by 8.4% while reducing environmental impact, lowering power prices, and increasing profits on fuel energy spent.

2.1.1. Summary

Cogeneration systems in sugarcane mills generate electricity and heat, increasing energy efficiency and lowering environmental impact. This eliminates reliance on external power sources and allows excess electricity to be sold back into the system. Cogeneration reduces greenhouse gas emissions while aligning with sustainability goals. Integration with existing facilities maximizes resource utilization and improves plant operations. Waste heat generated during the operation can be reused for various industrial processes, increasing efficiency. However, problems such as early investment costs, technological issues, and regulatory compliance exist. Despite these challenges, cogeneration benefits the sugarcane industry by boosting energy efficiency, lowering costs, and improving environmental sustainability.

2.2. Boiler Technique of Sugarcane Processing

The boiler technique in sugarcane processing is critical for extracting sucrose from juice, heating, evaporating surplus water, and powering steam turbines to generate electricity, all of which contribute to industry sustainability by lowering dependency on non-renewable energy sources. In the boiler technique of sugarcane processing, bagasse is utilized to generate steam, which is necessary for several milling processes as well as the generation of electricity. Using this technology, high-pressure boilers are fuelled by bagasse, a fibrous by-product of sugar production.

Burning the bagasse, these boilers transform their chemical energy into thermal energy, generating steam at high pressure and temperature. Following that, this steam has two primary uses: it powers steam turbines that generate energy and supplies process heat for sugar milling activities. Modern boiler systems include heat recovery mechanisms and cutting-edge combustion technology to increase performance and efficiency. Using these technologies reduces greenhouse gas emissions and the need for external energy sources, increasing sugar mills' overall sustainability and economic viability by optimizing the energy recovered from bagasse. The sugarcane industry's potential to achieve energy self-sufficiency and environmental sustainability through integrating high-efficiency boilers in cogeneration systems is exemplified.

Nemomsa, S. K et al. [31]; Bagasse, a sugar byproduct, produces high-pressure steam for energy generation. However, the moisture content can have an impact on boiler efficiency. Research at the Arjo Diddesa sugar refinery discovered that bagasse with more than 52% moisture content reduces boiler efficiency. The facility employs traditional SHRD technology to reduce moisture content via waste flue gas. A 52% reduction in bagasse moisture content to 45% results in a 71.5–74.5 percent increase in boiler efficiency. GCV and NCV at initialisation are 9137.6 and 7129.4 kJ/kg, etc. The GCV and NCV increase to 10484.8 and 8549.8 kJ/kg after drying.

Dias, M. C et al. [32]: The study aims to evaluate the energy efficiency of an aqua tube boiler in the south-central region of Brazil that employs bagasse from four distinct types of sugarcane. The efficiency will be determined using the PCI, PCS, and direct approaches. The findings highlight the importance of energy analysis for energy cogeneration and the benefits of regulated management throughout the manufacturing process. Intrinsic characteristics such as bagasse and moisture content determine optimal energy production effectiveness. It was shown that the SP 80-1816 variant was more beneficial since it uses less bagasse in the boiler feed, resulting in higher energy output.

Mazibuko, T. C et al. [33]; Steam boiler failures in South Africa greatly influence the country's GDP, resulting in load shedding and a loss of R59 billion in 2019. Machine learning models can predict boiler breakdowns and optimize performance while avoiding common failure reasons such as overheating. This may be relevant to South Africa's power facilities, which are vulnerable to malfunctions that cause blackouts. In order to operate the boiler and maintain a constant temperature distribution while preventing tube leaks, a study was repeated employing machine learning to forecast temperatures at different zones inside a boiler. The study demonstrates how feature selection can dramatically improve machine learning models' performance while simplifying them, making them easier for decision-makers and less computationally costly to re-train and apply.

Feliu-Batlle, V et al. [34]: This paper presents a reliable PIα controller for managing steam pressure in a bagasse-fired boiler's steam drum. Experiments demonstrate both dynamic behaviour and significant static gain fluctuations. A novel technique for fractional-order resilient controllers is proposed to achieve nominal time conditions while optimizing controller parameters to increase gain margin. In terms of integral absolute error and steam pressure uniformity, the controllers perform better than PI or PID controllers.

Murnandari, A. et al. [35]. The article delves into waste management in the sugar business, specifically the extraction of CO2 from boilers and its absorption into a process that produces calcium and magnesium carbonates at a daily capacity of 3000 tonnes simulations using Aspen® Plus determined heat duty, thermodynamic feasibility, and yield distribution. The technique generates 210 kilograms of CaCO3 every hour.

Machin, E. B. et al. [36]: The study examines the cost-effectiveness and environmental effects of building a BIG-GTCC in a Brazilian sugarcane mill. It recommends employing Torre faction technology for wet bagasse pretreatment to address feeding concerns. According to a life cycle assessment, gasification of plant bagasse is the most cost-effective and ecologically benign alternative regarding predicted annual revenue.

Olatunji P. Abolusoro et al. [37]: Biofuels can take the role of burning fossil fuels as the main energy source, according to a study on agricultural waste. The study used a fluidised bed to guarantee clean burning and lower greenhouse gas emissions. The results highlight the growing global demand for clean, inexpensive, and dependable energy as well as the necessity of employing agricultural waste as a sustainable energy source.

Onarheim, K et al. [38]: The study investigates hydrogen augmentation in rapid pyrolysis-based biorefineries to boost biofuel output. The findings show that using off-gases from pyrolysis to create synthetic natural gas while using an external hydrogen source can reduce biomass resource utilization by 48.2% for TFP and 61.2% for CAT. These hydrogen-enhanced designs improve carbon efficiency by 40.5% to 66.3% for TFP and 28.9% to 58.6% for CAT. Table 2 displays the methods, benefits, drawbacks, and outcomes of the Boiler Technique used in the sugarcane processing sector.

Table 2. Boiler technique of sugarcane processing industry

Ref. No.	Author Name	Technique	Advantages	Disadvantages	Results
33	Nemomsa, S. K (2023)	A study at the Arjo Diddesa sugar mill discovered that bagasse, a sugar industry waste, had a high moisture level of about 52%, which reduces boiler efficiency.	Bagasse and flue gas are channelled via the outer revolving cylinder, while steam is directed through the inner tube to minimize heat losses. Both direct and indirect flue gas-bagasse contact are the effects of this.	Bagasse's high moisture content affects boiler efficiency by needing extra moisture to evaporate before combustion, which increases fuel consumption, operational expenses, and overall cogeneration plant efficiency.	Wet bagasse can be transported using the SHRD system, slanted horizontally and rotated at 4.6 rpm. This reduces moisture from 52% to 45%, increasing boiler efficiency to 74.5% from 71.5. At 52% moisture content, bagasse's initial GCV and NCV were 9137.6 kJ/kg and 7129.4 kJ/kg, respectively. The GCV and NCV increased by 1500 kJ/kg after drying.
34	Dias, M. C (2020)	This study uses four sugarcane cultivars, SP 80-1816, RB72-454, SP80-3280, and SP81-3250, to examine the thermal efficiency of an aqua tube boiler.	The boiler model has advantages such as functioning with pressures ranging from 50 to 165 bar, producing steam quickly, requiring minimal start-up time, and adaptability to various fuel types.	The downsides of this system are its enormous size, susceptibility to load fluctuations, high feed water quality need due to high operational pressure, expensive installation costs, and complex assembly.	SP 81-3250 has a high PCI of 97.11%, indicating outstanding sugar extraction efficiency. SP 80-1816, with an efficient PCS of 82.47%, uses energy for constructive purposes.

35	Mazibuko, T. C (2020)	This paper presents instances of using machine learning models to forecast and optimize steam boiler performance, avoiding frequent failure mechanisms like overheating.	Machine learning algorithms may reliably forecast boiler performance by analyzing massive volumes of data from sensor readings, historical performance data, and ambient conditions, yielding more exact results than previous techniques.	ML models need a lot of high-quality data for training and validation. . In some circumstances, gathering enough data might take much work, particularly for older or less instrumented boiler systems.	The optimization model employing the IP algorithm and the SVR approach dramatically lowered temperature standard deviation by 42% and oxygen content difference by 61% compared to the original data, resulting in a 32% increase in temperature and a 38.6% drop in oxygen content, respectively.
36	Feliu-Batlle, V (2021)	This work presents a robust PI controller for regulating steam pressure in a bagasse-fired boiler's steam drum.	The PI controller assures stable operation by combining proportional and integral action, responding to current faults while reducing steady-state errors by considering previous ones, resulting in safe and efficient boiler operation.	Improper PI controller tuning can cause instability, oscillations, or sluggish response, compromising system efficiency and safety in complex systems with unknown dynamics.	At low gain settings, the PID and PI controllers exhibit comparable behaviour. At medium and high gain levels, the PI controller does, however, enhance steam pressure uniformity.
37	Murnandari, A (2020)	This study investigates the utilization of integrated waste in the sugar industry. In order to create mineral carbonates, carbon dioxide (CO_2) is collected from the boiler and absorbed into a mineral solution composed of filter cake (mud) that may produce three thousand tonnes of sugarcane daily.	PI controller enables stable operation by combining proportional and integral action, responding to current faults, and reducing steady-state errors, resulting in safe and efficient boiler performance.	Tuning a PI controller to obtain the desired performance can be difficult, especially in complex systems where the dynamics could be better understood or vary dramatically over time. Improper tuning can cause instability, oscillations, or sluggish response, compromising the system's efficiency and safety.	Mineralizing filter cake requires 74.2 kg of CO2 and 76.3 kWh of heat per hour for 2.8 tonnes of sugarcane, with a daily throughput of 3000 tonnes.
38	Machin, E. B (2021)	The study evaluates the environmental and financial viability of constructing a sugarcane mill in Brazil, as well as biomass-integrated gasification and a combined cycle of gas turbines for electricity generation.	BIG-GTCC systems improve efficiency by gasifying biomass, producing clean syngas for electricity generation, and using waste heat to power secondary steam turbines.	BIG-GTCC systems require a significant upfront investment in gasification, turbine, and combined cycle equipment, which may be a barrier to implementation for some sugarcane mills due to high capital expenditures.	According to the study, electricity generation accounts for just 63% of overhead costs, and the most significant economic barrier to pure to meet the plant's steam specifications, external bagasse availability is a prerequisite for implementing BIG-GTCC.

39	Olatunji P. Abolusoro et al. (2023)	The study focused on GS and SB's potential as solid biofuels for producing power and process heat, examining their clean combustion and low greenhouse gas emissions.	GS and SB are typical by-products of industrial processes in the sugar and biodiesel industries. Using these wastes as biofuels for energy production decreases fossil fuel dependency and encourages renewable resource use.	Fuel quality and composition of GS and SB feedstocks can vary due to moisture, ash, and particle size distribution, affecting combustion efficiency and needing constant monitoring and parameter modification.	Despite having identical combustion efficiency, GS has a Higher Heating Value (HHV) and excellent heat rate (501.05 kJ/kg) than SB (16029.88 kJ/kg).
40	Onarheim, K (2020)	In fast pyrolysis-based biorefineries which use quick and catalytic pyrolysis to convert bio-oil into petrol, diesel and heavy hydrocarbons hydrogen enhancement can boost biofuel output.	Hydrogen enhancement has the potential to dramatically raise biofuel production in rapid pyrolysis-based bio-refineries, increasing the overall output of valuable biofuels and boosting the process's economic feasibility.	The source of hydrogen utilized in biofuel production, whether from fossil fuels or electrolysis, can substantially impact the environmental footprint and sustainability of the process, potentially diminishing its total ecological advantages.	According to the study, using the off-gases from the pyrolysis process to create synthetic natural gas while using an external hydrogen source can reduce biomass resource utilization by 48.2% while improving carbon efficiency in hydrogen-enhanced designs.

2.2.1. Summary

Boilers are critical in sugarcane processing, allowing for effective juice extraction and energy generation. The mill produces steam by burning bagasse, a fibrous residue, as a sustainable fuel to run turbines for energy production and other industrial processes. Boilers have benefits such as higher sugar production, energy efficiency, and waste utilization, but they also have drawbacks such as expensive installation and maintenance costs, environmental problems, and technical complexity. Despite these challenges, boilers remain necessary for sugarcane processing, and good management and maintenance are critical to maximizing their benefits while minimizing their negatives. Overall, boilers are essential in keeping sugarcane mills running smoothly and contributing to sustainable energy production.

2.3. Turbine Technique for Power Generation in the Sugarcane Industry

In the sugarcane industry, steam turbine design is crucial for power generation utilizing biomass residue, particularly bagasse, to produce electricity. This section explores how the sugarcane sector uses this renewable resource for electricity generation. Utilizing steam turbines, the turbine technology for power production in the sugarcane industry converts thermal energy from high-pressure steam produced by burning bagasse into mechanical energy, which is subsequently converted into electrical energy. Steam turbines are aimed towards the high-pressure steam produced by bagasse combustion in boilers. The steam's thermal energy is efficiently converted into rotational energy by these turbines, which power a generator to create electricity.

The sugar mill can use this electricity to power itself, and any extra can be supplied back into the regional power system. Modern steam turbines are more reliable and efficient and perform better thanks to cutting-edge materials and design elements. By generating extra income from the sale of surplus energy, this cogeneration strategy not only maximizes the use of bagasse, reducing waste and dependency on fossil fuels, but it also helps sugar mills remain financially sustainable. As a result, the turbine approach is essential for advancing renewable energy and raising the sugarcane industry's total energy efficiency.

Abd El-Sattar, H et al. [39]: This study focuses on a tri-generation system that uses biomass to generate electricity, cool water, and heat. The cooling system comprises EFGT, ORC, and absorption, and the feedstock is Upper Egyptian sugarcane bagasse. The ORC uses Many fluids, such as R11, benzene, toluene, and cyclohexane. Toluene is the most efficient working fluid for applications that combine electricity, heating, and cooling. The system produces 177.56 kW of net electric power, 24.2% net electrical efficiency, 38.50 kW of cooling capacity, and 43.50% CCHP efficiency. Kabeyi, M. J. B. et al. [40] The study suggests a cogeneration plant, the Kipevu I diesel power plant, that generates energy from exhaust heat. The facility absorbs waste heat and turns it into electricity, providing a dependable backup power source. The study looks at the plant's reliability, design, scalability, and interfaces, which include the heat exchanger, boiler, steam turbine, and turbo generator. The boiler's steam is superheated in a heater, which drives the turbine and generates extra electricity.

Alba Y et al. [41] study looks at three options for using Marabou as feedstock in Cuba's sugarcane sector cogeneration facilities: traditional backpressure steam turbine cycles, turbines for extraction and condensation, and torrefied marabou. The findings show that A-3 has less of an impact on the environment in terms of water use, land acidification, and the production of fine particulate matter. The cogeneration stage has the most significant environmental impact, with marine Eco toxicity being the most ecologically favourable category. The study suggests that utilizing torrefied marabou as feedstock and extraction-condensing steam turbines as power sources could be a green technology in Cuba. Ahmed, A. H. et al. [42]; The first and second principles of thermodynamics and the Kirkuk unit were used to analyze a 150 MW gas turbine facility. The compressor, combustion chamber, turbine, and exhaust gases have first- and second-law efficiencies of 93.34% and 93.3%, respectively. The energy efficiency was 32.397%, while the total thermal efficiency was 33.069%. Sankei and Grasmann diagrams were used to illustrate the results, respectively.

Telini, R. et al. [43]: A Brazilian study uses a combined cycle integrated with Biomass Gasification (BIG-CC) and CEST to examine BECCS in sugarcane-based energy systems. The findings indicate that thermal power plants may have lower CO^2 collection costs than cogeneration systems due to potential scale effects and energy penalties. In the best-case scenario, capture costs might fall to EUR 54-65 per tonne of CO^2.

Zhang, H et al. [44]: A new cogeneration system is recommended to increase a coal-fired power station's power output and heating capacity. It is predicated on the Absorption Heat Pump (AHP) and Organic Ranking Cycle (ORC). The gadget generates energy by recycling waste heat from expelled steam into the AHP. When the heating extraction steam flow rate is 40 kg/s, the technique enhances the power generation and thermal capacity by 1.47 MW and 32,106.64 kW, respectively. The system utilises less coal when the thermal extraction flow rate increases and the load falls.

Vinay, K. B. et al. [45]; the rapid rise of vehicle engineering has considerably improved a country's socioeconomic standing, owing primarily to advances in energy. This has prompted a holistic approach to energy and its optimal utilization. The typical power generating technique only delivers around one-third of the primary energy to the customer as electricity. This needs the implementation of more complex technologies, such as cogeneration plants. Cogeneration has multiple advantages for various financial activities and can achieve an overall energy efficiency of 85 per cent or more extraordinary in certain circumstances. This paper examines the thermodynamics of a high-pressure boiler and energy auditing techniques. The techniques, advantages, limitations, and results of the steam turbine technique for power generation are shown in Table 3 below.

Table 3. Steam turbine technique for power generation

Ref. No.	Author Name	Techniques	Advantages	Disadvantages	Results
41	Abd El-Sattar, H (2020)	The goal of the project is to create a tri-generation system that utilizes direct combustion to turn biomass into heat, cooling, and electricity while incorporating a combustor chamber, EFGT, organic Ranking cycle, and absorption cooling.	Biomass is a renewable energy source, making the tri-generation system more ecologically friendly and lowering fossil fuel dependency, which helps mitigate climate change.	Modelling and executing a tri-generation system necessitates extensive technical competence due to the complexities of combining several energy conversion processes such as combustor chambers, gas turbines, organic Rankin cycles, and absorption cooling systems.	The ideal biomass consumption rate is 144 kg/h, with a net electric power output of 177.56 kW, a net electrical efficiency of 24.2%, and a cooling capacity of 38.50 kW.
42	Kabeyi, M. J. B (2021)	This study proposes a cogeneration facility to generate additional energy utilizing a steam turbine powered by steam generated from exhaust heat.	The cogeneration plant improves energy efficiency by converting exhaust heat into electricity via a steam turbine, maximizing resource utilization, minimizing waste,	The initial investment in equipment and infrastructure for cogeneration facility installation may be substantial. Still, the potential for long-term cost benefits outweigh the initial cost, potentially impeding	The cogeneration turbine is an extraction turbine with good part-load characteristics and can achieve up to 80% overall plant thermal efficiency.

			and boosting practical energy extraction.	deployment for some organizations.	
43	Alba, Y (2021)	The study looks into three environmentally beneficial solutions for Cuba's sugarcane industry's cogeneration facilities: traditional backpressure steam turbine cycles, torrefied marabou cycles, and extraction-condensing turbines, and evaluates their environmental impact.	Extraction-condensing turbines extract steam at varying pressure levels for diverse industrial processes, producing excellent energy conversion efficiency.	Because of their complex technology and additional steam extraction and condensing equipment, extraction-condensing turbines may necessitate a more significant initial expenditure.	The Torrefaction subsystem in A-3 has the most significant environmental impact, accounting for 94% of the total environmental load. This is primarily due to PM-10, NO2, and SO2 damage.
44	Ahmed, A. H. (2020)	The Dataflow sheet Kirkuk unit was used to perform energy on a 150 MW gas turbine facility and energy analysis.	Energy analysis is critical for engineers and operators to assess a gas turbine plant's efficiency, dependability, and efficacy in producing power.	Technical issues in energy analysis include data accuracy, measuring procedures, and modelling assumptions, which must be carefully considered and validated against actual data to assure dependability and validity.	The analysis showed that the first-law efficiencies of the exhaust gases, combustion chamber, compressor, and turbine were 42.32%, 85.52%, 94.11%, and 93.34%, respectively.
45	Telini, R (2021)	This study concentrated on carbon storage and capture in energy systems based on sugarcane and emphasized thermal power plants that employ CEST and BIG-CC technology.	CCS technology allows thermal power plants to absorb CO2 emissions before they are released, lowering the carbon footprint of sugarcane-based energy systems and helping to mitigate climate change.	CCS technology, particularly in thermal power plants using CEST and BIG-CC, can be complex, necessitating specialized technical solutions for integration into existing plant infrastructure.	The cost of CO2 capture may be reduced by integrating CCS systems into thermal power plants. The potential prices of CEST and BIG-CC technologies are estimated to be EUR 54–65 and EUR 57–68 per tonne.
46	Zhang, H(2020).	An innovative cogeneration system built on ORC and AHP technology boosts a coal-fired power plant's ability to produce electricity and heat.	When combined with the Organic Rankin Cycle, waste heat from coal-fired power plants and Absorption Heat Pump technologies can be used more efficiently, increasing energy efficiency.	The significant upfront investment necessary to establish ORC and AHP cogeneration systems may impede their adoption in some coal-fired power plants.	The study found that thermal and energy efficiency increased. The amount of coal used for heat transport and electricity generation decreased by 1.71% and 9.38%, respectively.
47	Vinay, K. B (2020)	This presentation covers the thermodynamics of high-pressure boilers and	The company benefits from cogeneration, which	Thermodynamics of high-pressure boilers and energy auditing procedures entail	Cogeneration has various financial advantages and can

		energy auditing techniques.	may generate up to 6 MW using a steam turbine.	sophisticated principles and computations that may overwhelm viewers without engineering or thermodynamic expertise.	achieve an energy efficiency of 85% or more extraordinary in certain conditions.

2.3.1. Summary

Steam turbine technology is essential to the sugarcane business since it uses biomass residual from the extraction process to generate energy. This process converts thermal energy to mechanical energy, ultimately converted into electricity via generators. Steam turbines reduce reliance on non-renewable energy sources, including fossil fuels, contributing to increased environmental sustainability.

They also help sugar mills attain energy self-sufficiency or surplus by selling excess electricity to the grid. Steam turbine technology also provides flexibility in power generation, allowing sugar mills to vary output based on demand or sugarcane availability. Advances in steam turbine design have increased electricity generation capacity and performance, maximizing sugarcane biomass utilization.

2.4. Factors Influencing Cogeneration Choice

The efficiency and financial sustainability of energy production are impacted by several factors that affect the cogeneration systems selected by the sugar industry. The kind and quality of the readily available biomass is crucial, especially for bagasse, the primary fuel. The moisture content and calorific value of bagasse can impact the efficiency of combustion and energy generation.

In addition, a significant factor in determining total performance and operating costs is the design and state of the cogeneration equipment, such as boilers, turbines, and generators. Because the current infrastructure is outdated and inefficient at maximizing energy output, upgrading it with high-pressure boilers and advanced turbines is often necessary.

Economic factors also influence decisions, including running expenses, capital investments, and the possibility of selling excess electricity. Regional factors also impact the decision-making process since they establish the viability and economics of various cogeneration systems. These factors include fuel availability, environmental restrictions, and grid connectivity. Finally, new technological developments, such as hybrid or integrated heat recovery systems, might influence the selection of cogeneration systems by providing increased sustainability and efficiency.

Hiloidhari, M et al. [46] The Life Cycle Assessment (LCA) of sugar production and bagasse power cogeneration, which is done from the field to the factory gate to analyze their energy and environmental performance, was given in this study. The ReCiPe 2016 midpoint (H) technique is employed for impact evaluation. System expansion is utilised to assess the alternative uses of sugarcane by-products (garbage, press mud, and bagasse ash). Out of these scenarios, combining a very high-pressure cogeneration boiler with ads sugarcane yields environmental advantages. The findings may help the Indian sugarcane industry's efforts to produce its products more cleanly. Variations in the data quality and regional variations in cogeneration technology and farming methods may constrain this process.

Arcentales-Bastidas, D. et al. [47] The study examines ethanol production from sugarcane in Ecuador, emphasizing cogeneration of energy, milling, distillation, and agriculture. Two functional units and OpenLCA v1.10.3 software are used. The study uses a hybrid attributional and consequential life cycle assessment technique to consider system expansion and economic allocation. Three possibilities are being looked at for the co-generation stage, which can potentially cause 53.6 kg of global warming, equivalent to carbon dioxide for every tonne of sugarcane produced. One of its limitations is this study's reliance upon particular regional data and settings, which might need to be more generally applicable or representative of other contexts or technology improvements.

A dynamic-integrated optimization technique taking into account the prevailing process dynamics and the heat and power coupling of the cogeneration unit was recommended by Pablos C et al. [48]. The methodology complies with applicable European legislation and has been tested in a simulated sugar mill equipped with a cogeneration system linked to the external grid. The operation under two tariffs (TOU and Spanish Day-Ahead rates) showed that a reduction of up to 5.41% of the costs is attainable for the research under consideration, compared to the traditional policy of maximum production and fixed energy prices. It could not adequately convey the intricacies of the natural world and the focus of this study, which could restrict the applicability of the results to different industrial environments or cogeneration configurations.

Júnior, J. C. F et al. [49] The study examines biomass technology, sugar and ethanol plants, and biorefinery layouts. It considers thermochemical procedures for producing syngas and biochemical pathways for producing lignocellulosic and biobutanol. Energy-wise, thermochemical techniques are more efficient and produce less carbon dioxide than other options. When every accessible bagasse is used for these alternatives, biochemical pathways become viable.

Lignocellulosic ethanol production is a more sustainable technique due to its improved performance. It might not consider differences in technology performance and biomass availability in various settings or the possibility that computational models could oversimplify intricate real-world processes. Aburto, J et al. [50] The study aims to determine whether gasification in a sugarcane mill can produce steam and power instead of direct burning. A boiler and steam turbines were used in Scenario 1 (S1), while gas and steam turbines were used in Scenario 2 (S2). The results showed that Scenario 2's energy production costs are lower at higher solid biofuel costs, enabling competitive pricing for electricity export to the grid. This study's shortcomings include its reliance on certain biofuel cost assumptions that might not account for regional differences in the market and its possible simplifying operational complexity in real-life scenarios. Table 4 shows the factors influencing cogeneration choice for generating the power.

Table 4. Factors influencing cogeneration choice for power generation

Ref. No.	Author Name	Technique	Advantages	Disadvantages	Results
48	Hiloidhari, M (2021)	Life Cycle Assessment (LCA) of bagasse cogeneration	Possibility to increase the sugarcane industry's cleaner production in India	Limited by disparities in the quality of the data, regional variations in technology, and farming practices	The range of bagasse electricity's WCP among the scenarios is 209 to 354 $m^3 MWh^{-1}$ 662.
49	Arcentales-Bastidas, D (2022)	Ethanol production from sugarcane using cogeneration	Detailed examination of the ethanol production process and possible decrease in greenhouse gas emissions	It depends on local settings and facts; it might not be appropriate in other situations or with new technological advancements	When the sugarcane output improved from 71 to 86 t/ha, there was a notable 10% decrease in the potential impact of particulate matter creation.
50	Pablos, C (2021)	Dynamic-integrated optimization strategy	Using an optimized cogeneration system, costs can be reduced by up to 5.41%	It may not adequately represent the complexity of the natural world, with limited application to various industrial settings or cogeneration configurations	maximum output and set power prices, demonstrating a possible 5.41% cost reduction
51	Júnior, J. C. F (2020)	Biomass technology in biorefineries	Sustainable lignocellulosic ethanol production and more effective energy generation with reduced CO2 emissions	Performance and biomass availability may change in different environments, and computational models may oversimplify real-world processes.	The value of the BGT case η value is 61.2%, but the similar variable for the ZRO case is 60.6%
52	Aburto, J (2022)	Gasification in sugarcane mills	Competitive power price for export, lower energy production costs at higher biofuel costs	It depends on specific biofuel cost assumptions that might not consider variations in regional markets or the potential simplification of operational complexity.	CEP reduces to 0.42 US$/ton

2.4.1. Summary

Energy efficiency, power factor correction, and the mitigation of electromagnetic interference and harmonic content impact the selection of cogeneration systems for Photovoltaic (PV) applications, especially in grid-connected systems. Maximizing the PV system's output and sustainability requires optimizing energy efficiency.

Power factor adjustment is necessary to minimize reactive power and related losses and guarantee that the system functions successfully within the grid. Minimizing harmonic content and electromagnetic interference is critical to preserve power quality and adhere to legal requirements. This will guarantee a seamless integration of the PV system with the current electrical infrastructure.

2.5. Support for Bagasse Cogeneration

In the sugar industry, bagasse cogeneration which uses the by-product of sugar extraction to create energy is an essential and sustainable technique. In cogeneration systems, bagasse the fibrous residue remaining after sugarcane juice extraction is frequently utilized as fuel. These systems use bagasse as fuel for high-pressure boilers that produce steam, combining heat and power production. Electrical energy is produced by the steam that powers turbines connected to generators.

In addition to supplying the energy required to run the sugar mill and lowering dependency on outside energy sources, the cogeneration process enables excess electricity to be exported to the grid, generating additional income. Bagasse cogeneration helps use a waste product that might otherwise add to environmental problems if incorrectly disposed of. By efficiently converting this waste into electricity, the sugar industry can reduce its carbon footprint, improve operational efficiency, and contribute to a more sustainable energy landscape.

Kabeyi, M et al. [51] This study examines the functioning of a traditional sugar factory, export potential and electricity generation. Boiler inefficiencies, backpressure steam turbines, and the excessive usage of steam turbine drives are among the problems. Significant cogeneration potential is found in the study, yet it needs to be more utilized. Increased production and export capacity require modernization, including purchasing high-pressure boilers, replacing inefficient backpressure boilers with more effective ones, and cutting back on the steam used in factories. The factory may purchase a 15 MW power plant if its output approaches the targeted levels. Not all sugar factories can likely employ the same operational techniques and equipment due to variations in these factors.

Ghani, H. U et al. [52] In Pakistan, bagasse-based power is becoming increasingly well-liked as a cost-effective, renewable, and ecological energy source. With an emphasis on the agricultural stage, this study examined the environmental costs of producing power-utilizing bagasse. Compared to grid mix electricity, bagasse-based energy outperformed it regarding global warming, the formation of fine particle debris and acidity of the soil, and the scarcity of fossil resources. But the quality of its ecosystem could have been better. An attractive substitute for environmental costs is power generated from bagasse.

In this study, Athira G et al. [53], India's waste product from sugarcane farms, sugarcane bagasse ash, has potential use as a cement substitute. Unfortunately, due to poor quantification and accessibility, its widespread use in Indian cement factories has not yet been accomplished. A study that contrasted bagasse ash with fly ash and slag provided a comprehensive database of bagasse ash availability in five primary states. Findings indicated a greater likelihood of bagasse ash sources close to cement factories. It might not consider differences in bagasse ash's composition and quality, which could impact its suitability as a cement substitute. It might also ignore logistical issues beyond locality, like the expense of processing and transportation.

Murugesan, T. et al. [54] This study examines the pozzolanic, chemical, and physical properties of sugarcane bagasse ash used in concrete. It was discovered that although bagasse ash delayed setting times and decreased workability, it boosted compressive and tensile strengths by 20%. The resistance of bagasse ash blended concrete to air, water, and chloride ion penetration was also investigated in this study. It may impact how well it substitutes for cement and difficulties translating research from the lab to real-world settings, like more extended setting periods and less workability.

Mohammadi, F et al. [55] The life cycle consequences of energy production in Iran are compared in this study from bagasse and cane waste through gasification, anaerobic digestion, and combustion. When it comes to lowering greenhouse gas emissions and exporting extra electricity to the grid, the combustion alternative offers the most promising results. In contrast, biogas generation and gasification might perform better environmentally. Data availability, dependability, and market maturity are more significant with the combustion option. This study may be subject to biases because combustion technologies have a more developed market and have access to more data than gasification and anaerobic digestion. Additionally, the study may only partially account for the variations in environmental performance across several effect categories. The generation of power using the bagasse cogeneration was tabulated in Table 5.

Table 5. Bagasse cogeneration for power generation

Ref No.	Author Name	Technique	Advantages	Disadvantages	Results
53	Kabeyi, M (2023)	Examination of Conventional Sugar Factory Performance	It finds substantial potential for cogeneration and suggests modernization for improved efficiency	Because sugar plants differ in equipment age and operating processes, the results could not apply to all of them.	Modern sugar factories use steam turbines with a 50 MW capacity, whereas small mills typically use turbines with a 6 MW electrical capacity.

54	Ghani, H. U (2020)	Evaluation of bagasse-based power's environmental impact	Enhances grid mix power in terms of acidification, particulate matter, global warming, and scarcity of fossil fuels.	Reduced ecosystem quality and research on environmental costs that may have overlooked economic factors	25% less weighted environmental price
55	Athira, G (2020)	Using sugarcane bagasse ash instead of cement	An extensive database on bagasse ash availability and a greater chance of sources close to cement factories	Possible practical problems must be considered, including processing and transportation costs and variances in bagasse ash composition and quality.	If brickmaking facilities were to employ the SCBA successfully created in these two states, it could save around 8500 TJ of energy.
56	Murugesan, T (2021)	Properties of bagasse ash in concrete	improves air, water, and chloride ion penetration resistance, and increases compressive and tensile strengths.	Reduced workability, longer setup times, and challenges connecting laboratory research to practical applications	It is reported that processed SCBA has a greater SAI than raw SCBA, which did not meet the minimal threshold of 75% to be categorized as pozzolan.
57	Mohammadi, F (2020)	Life cycle analysis of bagasse energy production	Combustion choice lowers emissions of greenhouse gases, exports surplus electricity, improves data accessibility, and matures the market.	Potential biases brought forth by the developed market and the availability of data for combustion could provide room for differences in environmental performance between categories.	The typical yield of biogas produced from cane and bagasse waste is 0.12-0.55 Nm^3/kg dry matter.

2.5.1. Summary

The sugar industry's support for bagasse cogeneration depends on several essential variables. Bagasse, a byproduct of sugarcane processing, can be used for cogeneration, improving sustainability and energy efficiency by using a single fuel source to produce heat and power. This approach reduces dependency on fossil fuels and greenhouse gas emissions while optimizing the use of the biomass resources that are now available. Implementing feed-in tariffs and renewable energy credits, among other financial incentives and laws, is another impetus for bagasse cogeneration uptake. Additionally, by lowering energy costs and creating new revenue streams from the sale of surplus electricity, the integration of cogeneration systems can increase the sugar mills' economic viability.

2.6. New Technologies Relevant to the Sugar Power Industries

New technologies that improve sustainability and efficiency are driving a revolutionary phase in the sugar power industry. The relevance of innovations like sophisticated cogeneration systems, which use sugarcane biomass to produce heat energy and electricity concurrently, is growing. Modern automation and control technologies also lower waste, enhance energy management and optimize production processes. More dependable power generation and improved grid integration are made possible using smart grid technology in conjunction with high-efficiency boilers and turbines. These developments encourage using renewable energy sources, reduce greenhouse gas emissions, improve environmental sustainability, and increase the sugar mills' economic viability. Watanabe, M. D. et al. [56] With a comprehensive harvesting system, this study uses process-based models to investigate the economic feasibility of recovering sugarcane straw. The research reveals that a number of variables impact the Internal Rates of Return (IRRs) of the different options, including the size of the industrial facility, the distance travelled by straw, the duration of the process, the efficiency of the dry cleaning mechanism, and the cost of electricity. According to the study, shorter straw transport lengths and industrial scale are associated with increased economic feasibility. Although some industrial operating situations may cause specific nonlinear effects, higher DCS efficiency can increase viability. This study considers the possibility of fluctuation in simulation results because of assumptions made in sensitivity analysis and the particulars of the industrial operation. It also finds the reliance on current power rates, which can significantly impact the project's economic feasibility.

Ou, L. et al. [57] The study evaluates the economic viability of a biorefinery that uses mechanical refining pretreatment and autohydrolysis to produce sugar from lignocellulosic biomass. The biorefinery generates surplus electricity that is sold, ensuring its energy independence. The Minimum Sugar Selling Price (MSSP) is $446 per metric ton. The study also looks at high-value goods like polyol and xylitol that can be made from by-products like dissolved hemicellulose and lignin. The analysis concludes that these products' high value justifies the additional cost even with the extra capital expenditure. It includes potential uncertainties in the recovery and recycling efficiency of costly chemicals like acetone and glycerol, as well as probable uncertainties in the yields of high-value coproducts like xylitol and polyol, which have a substantial impact on the process economics overall.

Birru, E et al. [58] The study examines operational energy-related factors in conventional and modern sugar mills to find areas for energy efficiency gains and possible exports of excess electricity. The two varieties have different power-to-heat ratios, according to the results. Electric drives, a high-pressure boiler, a backpressure turbine, and bagasse drying are ways to improve conventional mills. These changes have a thermodynamic effect that increases power generation; case 1 exhibits a slight improvement in cogeneration efficiency. Nine Brazilian districts could receive at least 30% more power from 19 rehabilitated sugar mills than their current installed capacity. It includes the notable variations in Levelized Cost of Electricity (LCOE) between various modification cases, which may affect the viability of implementing more sophisticated upgrades, and possible variability in regional economic and operational conditions that affect the generalisability of the results.

Dogbe, E et al. [59] This study evaluates the cogeneration system efficiency of a sugar mill by integrating the technologies of Organic Rankine Cycle (ORC) and Absorption Heat Pump (AHP) to recover waste heat. The sugar-drying unit, deaerator, and total system's irreversibility were reduced by 51%, 76%, and 0.14%, respectively. The AHP integration saved 0.833% of the burned bagasse. The ORC produced "green" electricity, which resulted in a 1.7% gain in energy efficiency the 8.3- and 6.3-year payback periods of the AHP and ORC, respectively, made them economically viable. It may not accurately represent the complexity of real-world operations, and the conclusions of the economic feasibility analysis differ greatly depending on how the market and the initial investment expenses changed.

Hassan, S et al. [60] Using a bacterial strain called Brevibacillus borstelensis STRI1, the study demonstrates how sugarcane molasses can be converted into bioelectricity using microbial fuel cell technology. In MFC, sugarcane molasses was utilized as the substrate and the strain as a biocatalyst. After ten days of operation, the voltage rose quickly, measuring 990±5 mV in an open circuit and 453±6 mV in a closed circuit. Starting with an initial concentration of 1632 mg/L as COD, the power density was 188.5 mW/m2.

After five days, COD elimination was 11.7%, and after the procedure, it was 81.7%. It covers potential scaling issues and variations in microbial performance in different environmental conditions that may impact the reliability of power generation from sugarcane molasses using microbial fuel cell technology. Table 6 illustrates several new technologies for generating power for the sugar power industry.

Table 6. New technologies relevant to the sugar power industries for power generation

Ref No.	Author Name	Technique	Advantages	Disadvantages	Results
58	Watanabe, M. D (2020)	Economic viability of sugarcane straw recovery using integrated harvesting system	It emphasizes increasing economic viability with shorter transport lengths and higher DCS efficiency and identifies factors affecting IRRs, such as industrial scale and transport length.	Because of assumptions and operational details, simulation results may differ; dependence on current power rates may affect viability.	Internal rates of return were 35–69%, 44–83%, and 54–99% annually when mills with initial sugarcane crushing capacity of 2, 4, and 8 million tonnes annually were considered.
59	Ou, L (2021)	Economic viability of biorefinery using mechanical refining and autohydrolysis	It provides energy independence, generates excess electricity, and high-value coproducts to offset additional costs.	Uncertainty in recovery efficiency and high-value coproduct yields; possible fluctuations in chemical recycling	The biorefinery that processed 2000 dry MT of biomass feedstock per day was the subject of the NREL investigation. In contrast, the biorefinery under investigation in this study has a capacity of 1500 dry MT/day.

60	Birru, E (2019)	Evaluation of energy-related factors in conventional vs. modern sugar mills	It finds opportunities for increased energy efficiency and the export of surplus electricity; different improvements enhance cogeneration.	Variability in LCOE between modification scenarios; local operational and economic circumstances may impact generalisability	The excess power falls between 8 to 36 kWh/TC and 58–104 kWh/TC.
61	Dogbe, E (2019)	Combining ORC and AHP to recover waste heat in sugar mills	It improves energy efficiency, lessens irreversibility, and is profitably achievable with payback periods of 6.3 and 8.3 years.	Real-world operational complexity might not be fully reflected, and changes in the market and investment could affect the economic viability of a project.	Through the production of “green” power up to 10% of the cogeneration capability, the ORC increased the cogeneration system’s energy efficiency by 1.7%.
62	Hassan, S (2019)	Employing microbial fuel cell technology to produce bioelectricity from sugarcane molasses	High voltage and power density are demonstrated, along with a notable elimination of COD using molasses as a substrate and a particular bacterial strain.	Variations in microbial performance and scaling issues may impact power generation stability.	The voltage recorded was 990±5mV in Open Circuit Voltage (OCV), increasing at a high rate over time and 453±6mV in closed circuit voltage (1000Ω) after ten days of operation.

2.6.1. Summary

New technologies increase the sugar power industry’s productivity, sustainability, and efficiency. Cogeneration innovations enable sugar mills to generate heat and power from biomass, increasing energy efficiency and decreasing waste. Sophisticated control and automation systems streamline workflows, raising productivity and reducing expenses. Improved bagasse utilization technologies, like gasification and high-efficiency boilers, optimize biomass energy recovery. Enhancements in water treatment and management also lessen resource use and their adverse effects on the environment. These technical developments improve the sugar power industries’ capacity to generate revenue and maintain a sustainable environmental footprint.

3. Overall Comprehensive Analysis and Discussion

This comprehensive research investigates sugar cogeneration electrical power systems, emphasizing three important paradigms: Combined Heat and Power (CHP), boiler, and turbine. Each approach is thoroughly assessed regarding its advantages, disadvantages, and possible contributions to sugar cogeneration power systems. Traditional CHP techniques used in sugar cogeneration power systems, including BIG-CC, SRC, BIG-GT, GTCC, and ORC, effectively extract relevant characteristics. However, complex processes like biomass gasification, syngas purification, and combustion pose obstacles. The heat generated in cogeneration processes is critical to improving overall system efficiency. Boiler approaches provide potential for overcoming the constraints of standard CHP systems. Innovations like SHRD, aqua tubular boilers, bagasse-fired boilers, and biomass-integrated gas turbines show promise. However, boiler systems may lose energy during combustion and heat transmission, resulting in inefficiencies and reduced system efficiency. Turbine approaches, such as EFGT, Steam Turbine, CEST, and Back Pressure Steam Turbine, provide another option for sugar cogeneration power plants. While providing long-term cost advantages, Tri-generation systems necessitate extensive technical knowledge and a considerable initial investment. Issues with energy analysis may hamper implementation. Overall, this research highlights the complexities and necessity of sugar cogeneration in power networks. At the same time, each solution has advantages and disadvantages; technological improvements and process optimization promise to increase efficiency and sustainability in the sugar cogeneration business. Table 7 offers a systematic summary of the findings and relevant variables about the choice of cogeneration and novel technologies in the sugar power sectors.

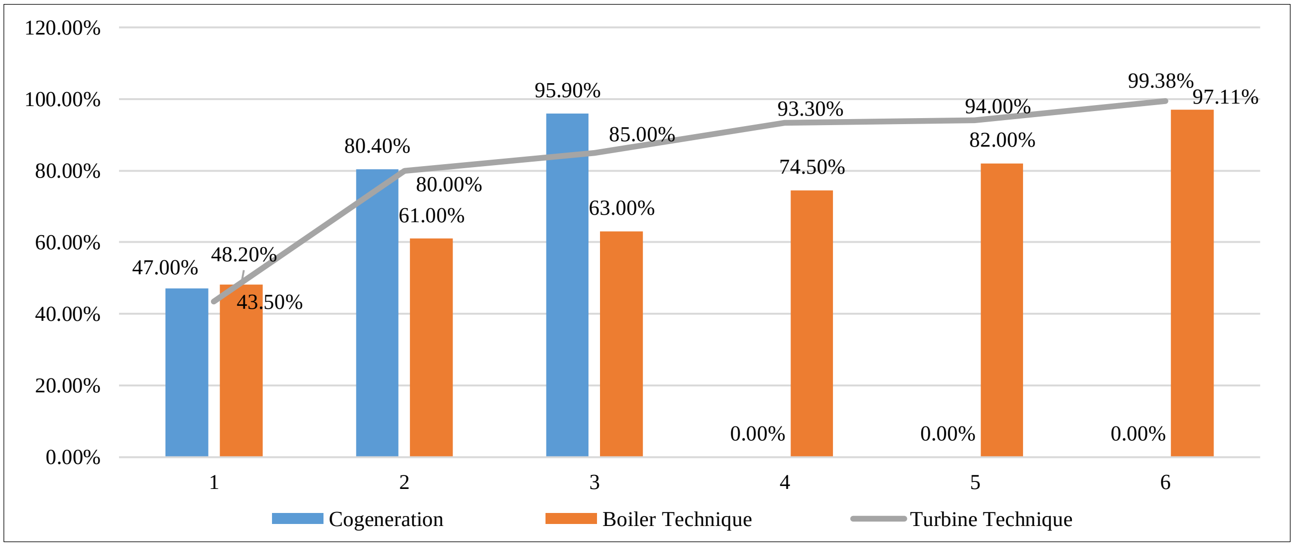

Fig. 1 Comparison graph based on techniques

Table 7. Power generation with several factors and its scenarios

Related Factor	Scenario/Data Point	Value/Description
Factors Influencing Cogeneration Choice	Water Consumption per Megawatt-hour (WCP) of bagasse electricity	209 to 354 m^3/MWh
	Particulate matter formation potential impact reduction	10% (with an increase in sugarcane output from 71 to 86 t/ha)
	Cost reduction potential	5.41%
	Efficiency (η) of BGT case	61.2%
	Efficiency (η) of ZRO case	60.6%
	Cost of Electricity Production (CEP)	0.42 US$/ton
	Capacity of modern sugar factory steam turbines	50 MW
	Capacity of small mill turbines	6 MW
	Weighted environmental price reduction	25%
	Energy savings with SCBA in brickmaking	>8500 TJ
	Strength Activity Index (SAI) of processed SCBA	Greater than raw SCBA (>75% threshold for pozzolan)
Support for Bagasse Cogeneration	Average output of biogas from cane and bagasse waste	0.12-0.55 Nm^3/kg dry matter
	Internal rates of return for mills (2, 4, 8 million tonnes capacity)	35–69%, 44–83%, 54–99% annually
	Biomass feedstock capacity (NREL study vs. current study)	2000 dry MT/day vs. 1500 dry MT/day
	Surplus power production	8–36 kWh/TC and 58–104 kWh/TC
New Technologies Relevant to the Sugar Power Industries	Energy efficiency improvement with ORC	1.7% (up to 10% cogeneration capacity)
	Open Circuit Voltage (OCV)	$990 \pm 5mV$ after ten days
	Closed circuit voltage (1000Ω)	$453 \pm 6mV$ after ten days

4. Conclusion

The content highlights the significance of cogeneration, boiler, and turbine processes in enhancing energy efficiency, cost reduction, and environmental sustainability within various industrial settings, mainly sugar factories. It underscores cogeneration as an effective method for simultaneous electricity and heat production, utilizing waste heat to improve overall energy utilization and process efficiency. Moreover, it emphasizes the role of boilers in supplying steam for cogeneration systems, stressing the importance of modern boiler technologies for optimal performance and integration within sugar refineries. Additionally, the content discusses turbines as key energy conversion components, emphasizing their efficiency and reliability in generating electricity from steam in cogeneration systems. It also underscores the importance of effective operation, maintenance, and management practices to maximize the benefits of cogeneration, boiler, and turbine techniques for sugar companies. Overall, the content advocates for careful planning, investment analysis, and operational management to fully exploit the potential of these strategies and their positive impacts on both industry and the environment.

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