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Research Article

A technique for determining the prices of steam and electricity generated in the sugar cogeneration industry

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ABSTRACT

Sugar Co-generation is the process by which steam and electricity are produced from a single fuel such as bagasse [1]. By burning bagasse,steam is produced at high pressure and temperature in the boiler. This high-pressure steam passes over the turbine and rotates the alternator to produce electricity and exhausted steam goes over the turbine at reduced pressure andis supplied to the sugar process, condenser, HP heaters, etc. Here delivered steam and generation of electricity are linear functions of the total steam produced in the boiler. During the season (generally October to March), sugar mills in India use their bagasse to run their mills and generate steam for the boilers and turbines. They generate electricity for their facilities & surplus power can be exported to the distribution licensees [9]. During the off-season, plant operations are stopped due to lack of bagasse therefore, particularly maintenance is carried out during this period. Nowadays, the plant remains in operation throughout the year by proper inventory management of bagasse.
In this study,the unit costs of the delivered steam and generation of electricity in a sugar cogeneration planthave been computed using the multiple linear regression least squares method. Without this regression method, it is quite difficult to calculate separately the unit cost of steam and electricity. The unit cost of every utility can be precisely calculated by formulating a mathematical model and fitting it to data taken from boiler logs. The multiple regression method makes it feasible to calculate the unit costs of delivered steam and electricity with accuracy. In this paper, the unit price of steam 5.2 Rs/kg and the unit price of electricity 7 Rs/ kWh is accurately determined by this method. The percentage relative error between the calculated and measured boiler steam delivery rates can be reduced with the use of the least squares method. This comparison's accuracy validatesthat the unit cost has been calculated correctly and that the model is appropriate. This multiple linear regression least squares method used in this paper has helped to determine the percentage relativeerror between measured boiler steam and calculated boiler steam. With this strategy, the standard deviation of the percentage relative error was found to be 0.53%.
In this paper, the Multiple Linear regression least square method is applied to a sugar Co-generation plant to calculate unit prices of delivered steam and electricity. It represents a linear relationship of delivered steam and electricity with total steam generated in the boiler. This concept depends upon the design of the plant output in which steam is to be collected at a lower pressure rate from the main turbine and is given to the sugar process, distillery process, etc. This method's accuracy is described by collecting actual plant data from the Pravara sugar Cogeneration plant, in Pravaranagar, India.

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INTRODUCTION

The sugar industry is the second largest agriculture-based industry in India and contributes significantly to the socio-economic development of the rural population. It supports 50 million farmers and their families and provides direct employment to over 0.5 million skilled and semi-skilled people in sugar mills and general industries. The Indian sugar industry plays a leading role in the global sugar market, being the second largest producer in the world after Brazil, producing nearly 15 and 25 percent of the world's sugar and sugar cane, respectively [2].

Since a few decades ago, there has been a severe lack of energy in India. The fundamental cause is the significant disparity between power supply and demand. As a result, the Indian government has encouraged cogeneration in the sugar industry. According to the Ministry of New & Renewable Energy (MNRE), Government of India research, the potential for producing electricity using bagasse co-generation at the national level is around 3500 MW. In contrast, it is only 1250 MW in Maharashtra. Indian Sugar Industries can produce up to 5000MW of excess electricity across all sugar mills.

Sugar industries have a large ability to contribute to sustainable energy transition through electricity generation and the production of biofuels. Sugar industries play a main role in the sustainable development of the nation. Sugar industries produce large volumes of bagasse from sugarcane specially used for electricity and steam generation [3,4].

Large co-generation Industries is advantageous and economical when they have heating and electricity facilities. This is especially true when the needs for electricity and heating are matched and when the demands for extracted steam and electricity work well together. Assigning unit charges to the two different types of utilities provided is an elusive challenge due to the mutually beneficial nature of the simultaneous generation of electricity and steam. One may argue that steam is effectively a "free" service because it is a by-product of the production of electricity and some of them argue that electricity is a free service because it is a by-product of generated steam.

However, this confusion can be avoided by assigning specific unit price values to both the generated electricity and delivered steam supplied whenever a plant has the choice of releasing steam from the turbines either at service pressure or at a vacuum. The cost of steam and electricity can be calculated by using multiple regression methods. Therequired data for the implementation of this method is taken from a plant during the operational period.

The cost may be expressed mathematically as a function of the amount of steam and electricity provided, and the model can be fitted to data from the boiler logs using the Multiple linear regression least squares method. This offers a mathematical approach for precisely calculating unit prices of steam and electricity. When consumption is metered within the plant or across the plants, it is essential to calculate unit prices for utilities produced by a plant accurately.

In this research paper, here multiple linear regression least square direct method is used for determining the prices of steam and electricity generated in the sugar cogeneration process. By implementing this method in sugar cogenerationmills we can easily calculate the unit price of the steam as5.2 Rs/kg and the unit price of electricity as 7 Rs/ kWh. It also helps to determine the percentage relative error between measured boiler steam and calculated boiler steam and it is to be found around 0.53%.

The novelty of the proposed strategy is that earlier researchers used the least square regression method in 'matrix form' for the computation of equations which is a very complicated method therefore it requires more time for the solution of equations. This proposed multiple regression method needs less computation time and gives more accurate results by solving only three equations. This method shows the linear relationship between electrical energy generation and delivered steam as a function of total generated steam in a boiler. Accordingly, the multiple regression method is used to calculate unit prices of steam and electricity in cogeneration plants.

Literature Review

Moses Jeremiah Barasa Kabeyi, Oludolapo Akanni Olanrewaju [1], in this research article author represents therole of sugar industries in the sustainable development of the nation. Sugar industries produce large volumes of bagasse from sugarcanespecially used for electricity and steam generation. In this paper author hasanalyzed the operation of traditional and modern sugar factories. According to the study, the factory uses old boilers that are extremely inefficient, which results in low power generation capacity and poor performance, and hence replaces low-pressureboilerswithhigh-pressureboilers. Traditional Steam turbines canalso be replaced by modern drives to obtain more output. Modernization is required in sugar industries to increase the generation and electricity export capacity through new and modern high-pressure boilers such as condensing extraction turbines (CEST) by replacement of inefficient back-pressure boilers (BPSB). Sugar factories can also make significant contributions towards the mitigation of greenhouse gas emissions through the supply of green electricity to the public grid.

Muhammad Umer, Inaam Ullah Mesum, and Abdullah Hashim Zahid [2], in this research paper author, have explained that Pakistan's electricity shortage has an extensive effect on its economic increase, people's livelihoods, and commercial operations. Currently, thermal methods like oil and gas satisfy around 67% of its power wishes, with hydropower generating 30% and nuclear approach producing the highest 3%. Bagasse, a stable waste produced at some stage in sugar production, is money owed for the simplest 0.9% of Pakistan's energy manufacturing. But, with the aid of enforcing co-generation retrofits, bagasse's capacity can increase up to 3000 MW. Sugarcane is a big crop in Pakistan, and sugarcane-crushing turbines have been utilizing boiler technology for many decades as a means of producing steam and producing energy. The process of cogeneration, which makes use of bagasse to generate steam and convey power, has several advantages, which include decreasing reliance on fossil fuels, providing a reliable supply of electricity, and a source of revenue for sugarcane generators. High-pressure boilers have numerous benefits, along with better strength efficiency, higher electricity generation, less wear and tear on equipment, and lower installation and maintenance costs. As most sugar mills are in rural areas we also can use this as a benefit and & provide power to remote regions. A case examination related to JDW Sugar mill has been added at the quit to examine the result of high- and low-pressure boilers. From the results, it is clear that if we want to have an efficient Cogeneration scheme in Sugar generators, we need to shift urgently towards high-pressure boilers.

Moses Jeremiah Barasa Kabeyi and Oludolapo Akanni Olanrewaju [3], in this proposed research, studied the Nzoia sugar factory which has a cane-crushing capacity is about 3000 tonnes per day and produces electricity for plant use only. The sugar industry must diversify to remain competitive given the high production costs and intense competition in the market. Supplying green electricity will increase the sustainability of the cane sugar industry and the electrical grid. We looked at the factory's and its cogeneration plant's performance to see if there was room for improvement and to diversify into exporting electricity to the public grid. The sugar industry, which is in crisis due to high production costs and sugar dumping, needs to diversify its business models. Export cogeneration has potential benefits in addition to diversification into ethanolproduction. Export cogeneration is another route for revenue generation for a struggling industry, in addition to diversification into ethanol production. An operational sugar factory's performance is analyzed in this study to ascertain its potential for producing electricity.

According to the study, the underutilized cogeneration potential has the potential to significantly reduce greenhouse gas emissions from power generation and generate revenue for the struggling sugar factory, thereby increasing its competitiveness. The plant's outdated, ineffective machinery has a very low efficiency, which adds to its poor performance. Three boilers that are more than thirty years old are producing inefficient amounts of steam. Export cogeneration will become more competitive and practical with the use of high-pressure, high-temperature boilers and a fuel substitute for bagasse as a secondary fuel. According to the study, a continuous cogeneration plant with a 15 MW capacity is advised at the current design milling capacity and average performance.

Moses Jeremiah Barasa Kabeyi [4], in this article, explains the sustainability measures to evaluate the environmental sustainability of different renewable electricity sources. Cost of generated electricity, greenhouse gas emissions over the full lifecycle, availability of renewable resources, energy utilization efficiency, land requirements, water use, and social and economic impacts were the sustainability indicators that were employed. Based on the premise that all indicators are equally important for sustainable development, the study ranked renewable energy technologies according to their effects. According to this study, geothermal, hydropower, photovoltaic, and wind energy are the most sustainable forms of renewable energy.

Jalili, M., Chitsaz, A., & Ghazanfari Holagh, S. [5],This research examined the energy consumption of a combined power and freshwater production facility powered by a combination of natural gas and biomass, or wood chips. The two other comparable systems that ran on pure natural gas and pure biomass had their energy indices compared with this system's. Every system was compared at the same output net power level to produce an accurate comparison. A multi-objective optimization technique was also used to improve the energy efficiency.

Moses J.B. Kabeyi [6], has identified the barriers to cogeneration in Kenya's sugar industry and suggested solutions. Technical, financial, and policy barriers to cogeneration were examined. The Kenya Sugar Board, Kenya Power and Lighting Company Ltd., Kenya Sugar Board, Ministry of Energy, and Kenya Electricity Generating Company Ltd. (KenGen) were the subjects of the study. It was established how much Kenyan sugar factories could produce. Data was gathered by observation, interviews, questionnaires, document analysis, and review. One major area of concern in this research was the potential use of sugarcane bagasse as a fuel for export-based cogeneration in Kenya's sugar industry.While cogeneration in the sugar industry has been around for a while; export-based cogeneration is a relatively new idea that hasn't been widely accepted, even in Kenya. The study found that the seven sugar factories in operation have a 586 GWhr export capacity at current capacity and efficiency. For the current production capacity, this capacity increases to 972 GWhr at a factory overall efficiency of 90%.Based on planned factory capacities and strategic plans to operate factories at 90% efficiency and high steam pressure of 82 bars, the potential is 1,803 GWh. But to reach this potential, it will be necessary to solve the existing financial, technological, and legal obstacles as well as regulatory issues.Improvements to processes to lower steam demand and electricity consumption while obtaining more steam for power generation, as well as a deliberate government policy to encourage export bagasse cogeneration through fiscal and regulatory measures to increase investments in bagasse cogeneration, were suggested as ways to facilitate export-based cogeneration.

Moses Jeremiah, Barasa Kabeyi [7], In this proposed research it was noted that the bagasse cogeneration project at Mumias Sugar Company has faced several difficulties that have forced the company to suspend operations when Kenya Power cut off electricity due to enormous electricity bills resulting from fines incurred for the cogeneration plant's failure to meet the terms of the power purchase agreement (PPA).Due to fuel shortages brought on by supply disruptions from strikes and a lack of cane, which resulted in protracted forced outages of the cogeneration plant and sugar mills, cogeneration has been severely impacted. The amount of bagasse that was left over after the cane was crushed was insufficient to keep the boiler operating and produce electricity continuously.To ensure that the factory has a sufficient supply of bagasse for the cogeneration plant to run, the cane suppliers must be encouraged to stick with the project and carry on with cane farming.One of the biggest obstacles to sustainable cogeneration is the cogeneration plant's single-fuel boiler. The factory's ability to produce power has declined and is no longer sustainable. However, multi-fuel boilers that operate on multiple fuels could ensure continuous power generation. The cogeneration plant with 34 MW capacity was intended to operate using a single high-capacity boiler and a single turbine prime mover. Because the entire plant must be shut down whenever maintenance or repairs are needed, this presents significant challenges for operation and maintenance in terms of ensuring consistency in power generation. Additionally, the single boiler uses a lot of fuel to operate, and when there is insufficient bagasse, the entire plant is shut down, which has an impact on cogeneration and the factory's ability to produce sugar.

M. J. B. Kabeyi and A. O. Oludolapo [8], in this paper author, analyze the performance of the cogeneration plant at Mumias Sugar Company in Kenya and recommend the development of a duel fuel cogeneration plant such as coal-bagasse cogeneration plant. Bagasse-based plant operation depends upon the availability of bagasse if it is not available,then plant operation gets stopped. By using coal-bagasse fuels in the cogeneration plant it remains continuous in operation, so that it will increase the efficiency, revenue, and profitability of the plant. Coal-bagasse-based cogeneration plants require significant investment in new and more efficient equipment for the boiler and fuel system.

Raashi Bhutani, Kusum Tharani, Sudha & Yashmita Tomar [9],explains the importance of the cogeneration system. Cogeneration systems serve two purposes electricity from steam using waste materials obtained during industrial processes and also process heat for industry itself. To have a significant increase in the generation capacity of power in sugar manufacturing plants, advanced cogeneration systems are utilized. These systems contain high-pressure direct combustion steam Rankine cycle systems and biomass integrated gasification combined cycle (BIG-CC) systems. This paper focuses on the use of the BIG-CC system along with bagasse and other sugarcane residues like press mud in the sugar industry in India. It is found that with the increase in temperature and pressure of the co-generator, the general power output and hence the efficiency of the co-generator unit increases gradually. However, over 60 bar pressure, in many high-pressure systems, there's a necessity for special development strategies along with the materials that can withstand the high pressure as well as high temperatures (over 450°C).

Sonaje N.P. and Deshmukh G.K. [10], state that in sugarcane plants, energy conservation is crucial. In the sugar industry, there are numerous opportunities to save energy. Energy auditing is a potent tool that has been used successfully and effectively in the design and performance assessment of systems that are related to energy. Additionally, there is a need to support energy production, consumption reduction, recycling economies, and environmental protection. As a result, along with energy cogeneration, energy efficiency, and conservation should be considered new energy sources.

Muhammad Arshad and Sibtain Ahmed [11], investigated the cost-saving potential of the bagasse plant, which is primarily used in sugar cogeneration plants to produce electricity and heat for the sugar-processing process. Production of heat and electricity depends on the quality and quantity of bagasse primarily used as fuel in the high-pressure boiler. The energy produced by a cogeneration plant is used in industrial processes, and any excess is exported to the national grid. Therefore, cogeneration facilities have the potential to result in significant cost savings and also contribute to lower environmental pollution. In Pakistan, the production of electricity from sugarcane bagasse is incredibly valuable because the sugarcane crop can be used to generate fuel, food, fibres, fodder, and fertilizer for future generations. Using cogeneration technology, 1000 kg of bagasse typically produces 0.450 MWh of electricity. In Pakistan, bagasse's estimated electrical potential ranges from 1598 GWh to 2894 GWh. The national policy on the matter is compared between the 1990 J-tariff and the 2013 biomass cogeneration policy. Cogeneration technology produces surplus electricity that can be used to meet household needs and create jobs in rural areas. The factories will have access to a sizable portion. Additionally, it will help in reducing the greenhouse effect brought about by oil-based generation

Atiqur Rehman and Azzamul Asar [12] studied the electricity generation potential in the sugar mills of Khyber Pakhtunkhwa. Their work focuses on the potential of electricity generation from bagasse produced in sugar mills of Khyber Pakhtunkhwa. This indicates a significant potential for electricity generation, which can help in mitigating the power shortage in the province. This paper presents four different scenarios to evaluate the electricity generation potential of sugar mills, which results in a range between 83 MW and 275 MW, depending on the crushing capacity and technology used in sugar mills. The analysis shows that generating electricity from bagasse produced by sugar mills can contribute its share towards reducing shortfall in the electricity.

Khan M. R. [13], has investigated that in Pakistani sugar mills' bagasse has a significant potential for producing thermoelectric power. The sugar mills have a lot of potential to increase their electricity production. As a substitute source of electricity for Pakistan to help with the current energy crises, the availability of bagasse in a mill allows for maximum electricity generation. The findings of this study can be replicated all over the world, especially in developing nations, to assist in resolving the energy issue.

Purohit P. and Michaelowa A. [14], described how the production of electricity in a sugar cogeneration plant solely depends on the availability of bagasse as fuel. Fuel is used in the boiler during cogeneration, which lowers carbon emissions and preserves the local environment. Finally, the availability of bagasse in the plant determines the potential of electricity.

S.N. Chaphekar [15], explored coal-based cogeneration. A case study of 24 MW coal-based cogeneration plants is discussed in detail. A future scope on bagasse-based cogeneration is also discussed. The increasing price of fossil fuels, the increasing need for power supply reliability and security, and the increasing demand for energy-efficient technologies tend to favor the application of small power generation solutions. An excellent approach to these solutions is to install a combined heat and power system that can be configured to operate under normal conditions to supply local power needs but with grid backup. The sugar industry is an excellent option for industrial cogeneration, according to numerous studies conducted in India and other countries. Benefits include an indigenous waste product that can be used as fuel, a comparatively low capital requirement, and enough sugar mills of a certain size and quantity to contribute significantly to the availability of electricity. Despite these benefits, cogeneration is still largely unrealized in most nations, including India. Extra power derived from bagasse Technology such as cogeneration is not entirely new. To close the ever-widening gap between the supply and demand of electricity, plants that have been commissioned and put into operation have proven to be successful.

Bhattacharyya SC, and Thang DNQ [16], are being done economic analysis on the cogenerationmillsin Vietnam, the co-generators' own needs for heat and electricity would be satisfied, and the export of extra electricity to the grid would have additional advantages. However, there is debate over the cost of buying electricity from the Electricity Board compared to sugar cogeneration, or vice versa.

C. Mbohwa [17], has shown the current status of the two Zimbabwean companies and has recommended projects that can enable the sugar industry to maximize its production of electricity for grid export. Incremental addition of new technology over time has been used in the sugar industry. A time has come for the sugar industry in Zimbabwe to chart a strategic course that will manage the evolution of technology in the sugar power plants most beneficially. The new turbo alternator should change the operating practices at the company and most of the old turbo alternators might become redundant. New technologies that are being researched in the sugar industry were highlighted to open wide the areas that the sugar companies can explore to improve their processes. More value can be added to the bagasse so that it can generate more power, using higher-pressure steam giving an extra 90–100 kWh per ton of cane.

Robert L. McMaster[18], in this proposed paper, used the least square method, to calculate the unit prices of steam delivered and electricity generated from sugar co-generation plant. Here, a mathematical method is used in which required data has been taken from the boiler logs table to calculate accurately the unit Prices of each utility. This multiple regression least square method reduces the error between measured boiler steam and calculated steam. This comparison's accuracy confirms the model and the unit costs of utility were calculated properly.

In this article, unit prices of delivered steam and electricity can be determined by using multiple regression the least square method. This method is the extension of the ordinary least-squares (OLS) regression method because it involves two or more independent variables with one dependent variable. This mathematical model is completely based on a plant design. This method shows the linear relationship between two independent variables with one dependent variable. In the sugar cogeneration plant, primary fuel such as bagasse is burnt in a high-pressure boiler to produce high-pressure steam which is to be enforced on the turbine to rotate the alternator of course to generate electricity and exhausted low-pressure steam from the turbine used for the sugar process as shown in Figure 1. Here delivered steam and electricity generated are independent variables and steam produced in the boiler is a dependent variable. This means the total steam produced in the boiler depends on the delivered steam for the sugar process and electricity generated by the alternator.

In the Previous research paper, Robert L. McMaster [18], 24 months of plant data is taken into account where the least squares method with Matrix Form is used. Here plant data for 24 months of operation is to be considered, therefore there are 24 equations and 3 unknowns. These 24 equations are solved by the least squares matrix method which is very complicated. Hence by using the multiplelinearregressionleast square direct method, these 24 equations are placed only in three equations from which to calculate 3 unknowns. So that overall calculation by this method becomes simple, accurate, and less time-consuming.

The article highlights the following contributions:

1. In this current paper, the cost of steam and electricity can be calculated by taking the actual plant data for 4 months of operation from the Pravara Sugar Mill. This multiple regression method calculates the three unknowns such as internal steam usage (MT), steam Delivered ratio (boiler steam per delivered steam),and electrical steam ratio (steam in boiler per kWh electricity delivered).
2. Many researchers have used multiple regression the least square regression method in 'matrix form' for the computation of equations which is a very complicated method therefore it requires more time for the solution

of equations. This proposed multiple regression method needs less computation time and gives more accurate results by solving only three equations.

3. This method shows the linear relationship between the independent variables such as electrical energy generation and the delivered steam with the dependent variable as total generated steam in the boiler. Hence, the multiple linear regression least square method is used to calculate unit prices of steam and electricity in the cogeneration plants.
4. Multiple linear regression (MLR) is a statistical deterministic procedure that is utilized to study the phenomena in sugar cogeneration plants.
5. This information helps the plant to plan economic ways to produce steam and electricity and contributes in cost reduction of steam and electricity.

OVERVIEW OF SUGAR COGENERATION SYSTEMS

Sugar Cogeneration is the concept of producing two forms of energy from a single fuel such as bagasse. One form of energy must always be heat and the other form can be electrical or mechanical energy [13,14]. In a typical power plant, bagasse fuel is burned in a boiler to produce high-pressure steam that is used to turn a turbine, which in turn drives a generator that runs through the steam turbine to produce electricity. The exhaust steam is usually condensed into water that is returned to the boiler. Because low-pressure steam loses a large amount of heat during condensation, the efficiency of conventional power plants is only about 35%.In a sugar cogeneration plant, very high efficiency levels, around 75 to 90%, can be achieved. This is because the low-pressure exhaust steam leaving the turbine is not condensed but is used for heating purposes in factories or households [5].

Cogeneration systems are often categorized based on the order in which energy is used and the operating schemes that are used. Based on energy use, a cogeneration system can be categorized as a topping or bottoming cycle. In a topping cycle, the fuel is utilized to generate power initially, followed by thermal energy, a cycle by-product used to meet additional thermal needs such as process heat [8]. The most common type of cogeneration is topping cycle cogeneration, which is utilized extensively.A typical bagasse Sugar cogeneration plant is shown in Figure 1.

Topping Cycle

In a topping cycle, fuel is burned to release energy, which is then utilized to generate electricity. The process heat or other thermal energy needs are subsequently supplied by the heat that is exhausted from the power generating unit. Usually, this thermal energy is low temperature, low-pressure heat. This kind of heat is commonly used in drying, distillation, concentration, space heating, and cooling, among other processes [9].

In a topping cycle cogeneration system, prime movers other than gas turbines include steam turbines and internal combustion engines. The cogeneration system's choices could be any of the following i) Boiler/steam turbine ii) Internal combustion engine or waste heat recovery boiler (iii) Gas turbine or waste heat recovery boiler and (iv) Waste

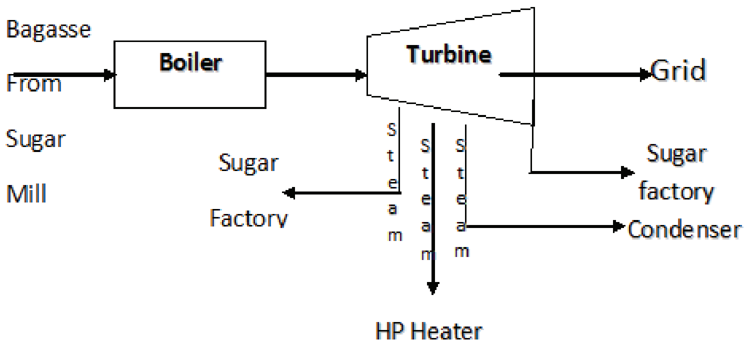

Figure 1. Bagasse cogeneration.

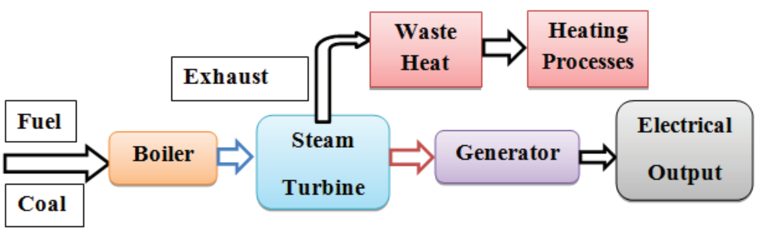

Figure 2. Topping system.

heat recovery boiler/gas or steam turbine. The combined cycle also referred to as the waste heat recovery boiler/gas or steam turbine, is widely employed by power utilities to increase the overall efficiency of their power plants. Figure 2 illustrates this.

Bottoming Cycle

In this cycle, the fuel is burned first to meet the needs for process heat, and the waste heat that is released during the process is typically used to produce power, either mechanical or electrical.

Typically, high-grade thermal energy that is, steam at high pressure and temperatureis employed in bottoming cycles. For instance, bottoming cycle systems reject waste heat noticeably at high temperatures, making them suitable for certain manufacturing processes that call for high-temperature heat in furnaces. There exist multiple methods to produce energy from this waste heat .A standard bottoming cycle cogeneration system with a steam turbine serving as the prime mover is depicted in Fig. 3.

Steam bottoming systems and organic fluid bottoming systems are the two main kinds of bottoming cycle cogeneration systems utilized in industrial applications. Steam bottoming systems are typically used when there is a significant amount of exhaust stream available at a temperature greater than 250 °C. The organic fluid, which has a lower boiling point than water, is utilized in the bottoming cycle if the temperature of the available waste heat is less than 250 °C.

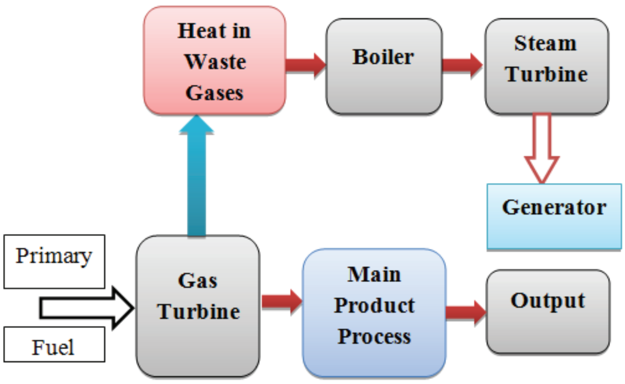

Figure 3. Bottoming system.

Table 1. Properties of bagasse

Compositions	Percentage (%)
Fiber	43-52%
Water	46-52%
Soluble solids content	2-6%
Average Density	150 kg/m^3
High-heat value	154,000 kcal/kg
Low-heat value	141,780 kcal/kg

Quantity and Quality of Bagasse

Bagasse is mostly fibrous, with a non-fibrous substance inside termed pith and a moisture level of about 50%. It has a 2300 kcal/kg calorific value. Bagasse represents 30–35% of the sugarcane crushed while the production rate of sugar is approximately 10-12% of the entire cane crushed [6,12].

Bagasse, filter mud, molasses, and other by-products are produced by sugar mills. For instance, a typical sugar plant with cane crushed per day is of 3,000 tons can produce refined sugar in the amount of 345 tons, alcohol in the amount of 6,000 litres, yeast in the amount of 3 tones, potash fertilizer in the number of 15tones, pulp in the amount of 25 tons, wax in the amount of 15 tons, and press-mud fertilizer in the amount of 150 tons. After sugarcane is crushed and its juice is extracted, bagasse is produced in a fibrous nature. The content of bagasse varies depending on the kind and quality of sugarcane used, as well as the methods of harvesting employed in the sugar mill to process the sugarcane. Usually, bagasse is burned in a boiler to generate steam and electricity in sugar cogeneration plants. Bagasse is also utilized as a primary raw material for paper manufacture as well as for feeding livestock [7,8].

Details of the Pravarasugar Cogeneration Plant

Pravara sugar plant is a cooperative sugar mill situated at Pravara village in Ahmednagar District. (Maharashtra State). This plant has a capacity of 30MW with a cane crushing capacity of 7,200 TCD. In this plant energy efficiency has been increased by the use of quality bagasse [10].

During the season, more quantity of bagasse is produced in the sugar process which can be used for plant operation and extra bagasse can be stored in the plant warehouse itself. During the off-season, plant operation has been stopped due to a lack of bagasse therefore for continuous operation of the plant bagasse can be collected from nearby mills or warehouses. The details of the Plant are given in Table 2 below.

Pravara Sugar Plant Operatıons in Season 2021-2022

Generally, this plant remains in operation for four months as per the availability of sugar cane and bagasse. During the operating period, necessary information such as total power generation, total power export, total steam

Table 2. Pravara plant details

Bagasse	2051.28 TPD (28.49% on sugarcane)
White sugar	884.88 TPD (12.29 % of sugarcane)
Bagasse Requirement	54 TPH for 7200 TCD capacity
Boiler capacity of 160 TPH	Steam pressure of 110 Kg/cm^2.
Power requirement	23 kWh
Molasses	272.88 TPD (3.79 % on cane)
Pressmud	266.4 TPD (3.70% on cane
Operational days	Average 160 -180 days

Table 3. Pravara sugar plant operation for 4 months in season 2021-2022

Plant output during operation	Season operation (2021-2022): From 16 November 2021 to 12 March 2022
Total generation of power	22706000 KWh
Total export power	12366622 KWh
Total steam in boiler (inlet turbine)	136600 Metric tons
Total steam has been given to the sugar process (delivered steam)	110477 Metric tons

Table 4. Monthly plant output (season 2021-2022)

Month	Delivered steam (MT) [x]	Generation of electrical energy (kWh) [y]	Steam in boiler (MT) [z]
November2021	28510	5853200	35350
December2021	28300	5685000	34520
January 2022	26500	5716500	33130
February 2022	27167	5451300	33600
Total	∑x =110477	∑y = 22706000	∑z =136600

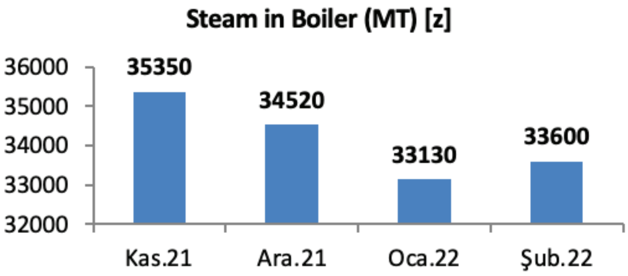

Figure 4. Shows the monthly steam generated in the boiler from bagasse.

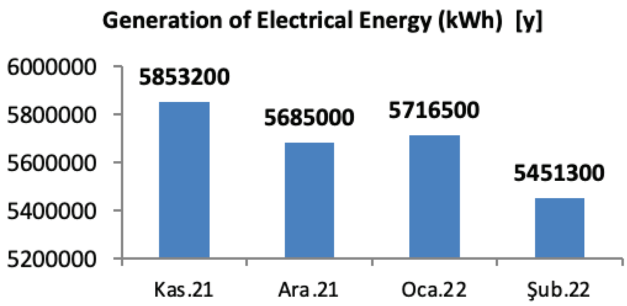

Figure 6. Shows the monthly electricity generated from boiler steam.

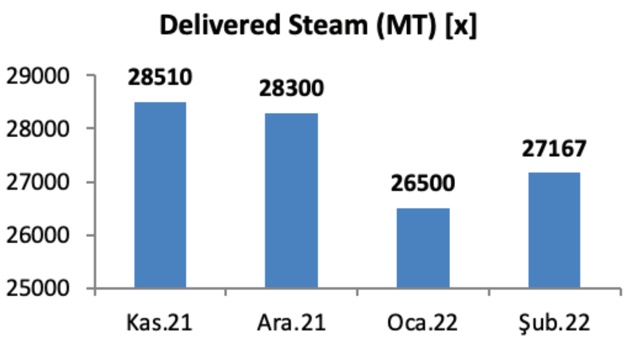

Figure 5. Shows the monthly steam delivered to the process.

generated in the boiler, and total steam utilized for the sugar process is collected from the plant. This information is essential to calculate the unit prices of delivered steam and electricity by using the multiple regressions least square method. This method represents a linear relationship between electrical energy generation and delivered steam as functions of generated boiler steam. The concept is based on a design of the plant that enables steam to be collected at a lower pressure from between stages of the generating turbines and utilized to serve heating loads. A high-pressure turbine can be employed in place of a low-pressure one to increase plant efficiency [10,13].

RESULTS AND DISCUSSIONS

Multiple Linear Regression Least Square Direct Method

Multiple regression estimates the outcomes (dependent variables) which may be affected by more than one control parameter (independent variables) or there may be more than one control parameter being changed at the same time [21,22].

An example is the two independent variables x and y and one dependent variable z in the linear relationship case:

$$z = a + bx + cy$$

For a given data set $(x_1, y_1, z_1), (x_2, y_2, z_2), \ldots (x_n, y_n, z_n)$, where $n \geq 3$, the best fitting curve f(x) has the least square error, i.e,

$$\prod = \sum_{i=1}^{n}(zi - f(xi, yi))^2 = \sum_{i=1}^{n}(zi - (a + bxi + cyi))^2 = min$$

Please note that a, b, and c are unknown coefficients while all x_i, y_i and z_i are given. To obtain the least square error, the unknown coefficients, b, and c must yield zero.

first derivatives.

$$\frac{\partial \prod}{\partial a} = 2\sum_{i=1}^{n} [z_i - (a + bx_i + cy_i)] = 0$$
$$\frac{\partial \prod}{\partial b} = 2\sum_{i=1}^{n} x_i[z_i - (a + bx_i + cy_i)] = 0$$
$$\frac{\partial \prod}{\partial c} = 2\sum_{i=1}^{n} y_i\,[zi - (a + bx_i + cy_i)] = 0$$

Expanding the above equations, we have

$$\sum_{i=1}^{n} z_i = a\sum_{i=1}^{n} 1 + b\sum_{i=1}^{n} x_i + c\sum_{i=1}^{n} y_i$$
$$\sum_{i=1}^{n} x_i z_i = a\sum_{i=1}^{n} x_i + b\sum_{i=1}^{n} x_i^2 + c\sum_{i=1}^{n} x_i y_i$$
$$\sum_{i=1}^{n} y_i z_i = a\sum_{i=1}^{n} y_i + b\sum_{i=1}^{n} x_i y_i + c\sum_{i=1}^{n} y_i^2$$

The unknown coefficients a,b, and c can hence be obtained by solving the above linear equations.

Multiple regression equations evaluate the results (dependent variables), which may be influenced by several variable control parameters (independent variables), or different control parameters may change simultaneously. Here in multiple regression least square equation shows a linear relationship of two independent variables (x and y) with one dependent variable (z) [18].

The objective of this Multiple linear regression method is,

- Forecasting the dependent variable from two or more independent variables.
- It shows the linear relationship between two or more independent variables with one dependent variable.
- It shows the relation between a dependent variable and two or more independent variables.
- It is extensively used for cost reduction and financial planning.
- It is used for proper control of either the import or export of electrical power in the plant.

Multiple Regression the Least Square Direct Method Applied for Sugar Cogeneration Plant As

Steam produced in a boiler depends on delivered steam and electricity generated. A linear relationship of delivered steam and electricity to be generated is shown with steam produced in the boiler. Here Steam in the Boiler is a dependent variable whereas delivered steam and electricity are independent variables in the equation (1).

$$z = a + bx + cy \qquad (1)$$

here,
z = Steam in Boiler (MT)
a = Internal use of steam (MT)
b = Ratio of steam delivered (ton of steam in boiler per ton steam delivered)
x = Steam Delivered (MT)
c = Steam to electricity ratio (MT/kWh).
y = Electricity delivered in kWh
Equations are as,

$$\sum z = na + b\sum x + c\sum y \qquad (2)$$

$$\sum xz = a\sum x + b\sum x^2 + c\sum xy \qquad (3)$$

$$\sum yz = a\sum y + b\sum xy + c\sum y^2 \qquad (4)$$

where n= plant operation period in months = 04

Use sample data from the above table in equations (2), (3), and (4) and we get equations (5), (6), and (7)

$$136600 = 4a + b*110477 + c*22706000 \qquad (5)$$

$$3775500700 = a*110477 + b*3054005989 + c*6.273429*10^{11} \qquad (6)$$

Table 5. Sample data calculations in tabular form as below

S.N.	xz	x^2	xy	yz	y^2
1	1007828500	812820100	$1.66847x10^{11}$	$2.06910x10^{11}$	$2.19x10^{13}$
2	976916000	800890000	$1.60885x10^{11}$	$1.96246x10^{11}$	$2.20x10^{13}$
3	877945000	702250000	$1.51487x10^{11}$	$1.89387x10^{11}$	$2.18x10^{13}$
4	912811200	738045889	$1.48095x10^{11}$	$1.83163x10^{11}$	$2.11x10^{13}$
Total	∑3775500700	∑3054005989	$\sum 6.27342x10^{11}$	$\sum 7.75708x10^{11}$	$\sum 1.2897x10^{14}$

$$7.75708145*10^{11} = a*22706000 + b*6.273429*10^{11} + c*1.2897*10^{14} \quad (7)$$

Solving equations (5), (6), and (7) we calculate unknowns a,b, and c as :

a=2.473,b=0.9023, c =1.19001*10^{-3}

equation as

z = 2.473+0.9023x+1.19001*10-3y

MATLAB Results

a = 1.0e+003*

a= 2.473000851301880

b= 0.000902336827360

c= 0.000001190017217

Determining the Steam and Electricity Unit Prices by Modelling the Sugar Plant's Output

It is necessary to create a mathematical model that accounts for the fuel used with the utilities given to determine unit prices for the electrical and steam utilities. Even if no utilities are produced at all, we are aware that there are costs connected with running the facility. The Plant administration is responsible for paying the staff's salary, service cost for maintenance work, and any depreciation expenses related to the plant's initial construction, whether or not the plant is actually in use. These can all be grouped under the heading "fixed costs."

In plants, the cost of fuel is the single highest expense related to plant operation, and a portion of this expense can also be treated as a fixed cost. A certain quantity of fuel is used and "lost" in the form of heat losses through piping and other types of equipment, electrical energy can be used to light the plant, etc. Since they are incurred regardless of the amount of plant production, these costs can be described as fixed costs.

Even if it is difficult to transform fixed costs for the delivery of electrical and steam energy into unit prices, it is nevertheless preferable to recover these expenses by charging consumers unit charges for the utilities they use. These expenses are readily considered in the boiler steam unit cost, which is subsequently assigned to the electricity and steam unit prices. The entire cost of a boiler steam unit may be calculated by dividing the total annual plant expenditures by the tons of boiler steam produced. An equation is written below [18].

$$\mathbf{Cbs} = \frac{\mathbf{ymain+yopp.+yfuel+\cdots+ycont.}}{\mathbf{z}} \quad (8)$$

where

Cbs - Unit price of boiler steam (in rupees per ton).

$y_{main.-}$ Yearly staff maintenance cost.

Yopp -YearlyOperating Cost

y_{fuel}- Plant's yearly fuel expenses.

Ycont -Yearly contract and service costs.

z -Yearly Steam Production in Boilers (tons).

$y_{fuel} = 7500 * 10^5$ Rs $\quad y_{main..} = 40 * 10^5$ Rs

$y_{oppo} = 70 * 10^5$ Rs $\quad y_{cont..} = 140 * 10^5$ Rs

$y_{sta} = 12 * 10^5$ Rs $\quad y_{ext.} = 100 * 10^5$ Rs

$y_{elect.} = 15 * 10^5$ Rs $\quad y_{total..} = 7877 * 10^5$ Rs

$$\text{Cbs} = \frac{\mathbf{y_{total}}}{\mathbf{z}}$$

$$\text{Cbs} = \frac{7877 * 10^5}{136600}$$

$$\text{Cbs} = 5766.47 \text{ Rs./MT}$$

$$\text{Cbs} = 5766.47 * 0.9023$$

$$\text{Cbs} = 5203 \text{ Rs./MT}$$

$$\text{Unit Price of Steam} = \text{Cbs} * \text{ b} = 5.2 \text{ Rs./Kg}$$

Now,

$$\text{Cbs} * \text{c} = 5766.47 * 1.19 * 10^{-3} \text{Rs./kWh}$$

$$\text{Cbs} * \text{c} = 7 \text{ Rs./kWh}$$

$$\text{Unit Price of Electricity} = \text{Cbs} * \text{c} = 7 \text{ Rs./kWh}$$

Percentage of Relative Error in Boiler Steam

Here put values of a, b & c in the below equation,

$$z = a + bx + cy$$

The % relative error can be calculated as,

$$\% \text{ Relative error } = \frac{\text{z(measured)}-\text{z(calculated)}}{\text{Zmeasured}} * 100 \quad (9)$$

Table 6. Percentage relative error (for 4 months of plant operation)

Month	Measured boiler steam[z] (MT)	Calculated boiler steam [z] (MT)	%Relative error
November 2021	35350	35162.87	0.53
December 2021	34520	34773.24	-0.73
January 2022	33130	33186.58	-0.16
February 2022	33600	33472.82	0.38

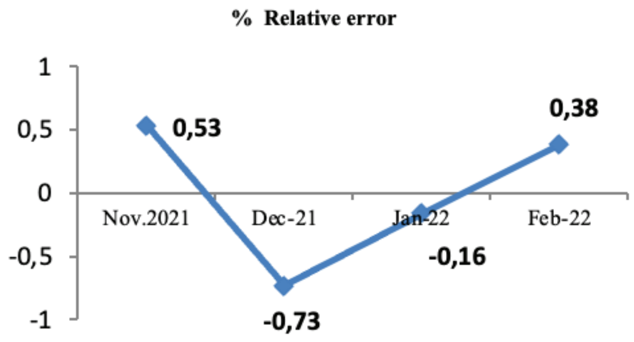

Figure 7. Percentage relative errors.

Examining the monthly difference between calculated boiler steam and measured boiler steam production may be used to calculate percentage relative error. This percentage relative error in boiler steam is represented graphically which is evenly distributed on both sides of the axis.

Before the implementation of this method of least squares, the plant used a trial-and-error method. Using this strategy, the standard deviation of the errors was 0.53 percent. The mathematical model may be made to be more comparable to the actual data since the regression method of least squares gives a more accurate answer for the parameters [19-23].

CONCLUSION

All Sugar cogeneration plantswork on a topping cycle in which steam is usedto generate electrical power first and thelow-pressure steam is used for the sugar process. It is quite challenging to determine the unit cost of delivered steam and electricity from a sugar co-generation plant. This multiple linear regression least square method used in this paper has accurately determined the unit price ofsteam 5.2 Rs/kg and the unit price of electricity 7 Rs/ kWh.

Data must be meticulously collected from boiler logs because, for any statistical method, the input data plays a big role in correct scientific analysis. This multiple linear regression least squares used in this paper has helped to determine the error between measured and calculated boiler steam. With this strategy, the standard deviation of error was found to be 0.53%.

Generally, there is a price difference in electric power between the cogeneration plant and the Electricity Board while sending and receiving power from and to the plant during off season and working season. These issues can be solved by calculating the exact cost of steam and Electricity. This is useful to fix tariff rates of energy in cogeneration plants and amongst other plants.

Once the cost of steam and electricity generated from the sugar cogeneration plant is calculated then it is useful to decide the plant's financial policysuch as energy demand and supply, energy security, Energy analysis, and management. This will be useful to increase plant efficiency and cost benefits.

Future Scope

This multiple linear regression least square method is the first time used in this paper for the performance analysis of a sugar cogeneration plant which can be utilized for future planning for cost saving indifferent types of cogeneration plants such as pulp and paper, cement, oil, steel and chemical plant etc.This method also helps to plan better economic policies in the cogeneration plants.

NOMENCLATURE

MNRE	Ministry of New & Renewable Energy
OLS	Ordinary least-squares
TCD	Tonnes in a day
MT	Metric Tonne
RES	Renewable Energy Source
PPA	Power purchase agreement
MLR	Multiple linear regression
CEST	Condensing extraction turbines
BPSB	Back pressure boilers
Rs	Indian Rupees

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AUTHORSHIP CONTRIBUTIONS

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

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

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