Statistical Modeling of Steam Generation for Cogeneration in Indian Sugar Industry: A Case Study

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ABSTRACT

The sugar industry is attaining new dimensions in the fast changing world. It is poised to play a much higher and wider role. Performance and productivity of the sugar industry plays a vital role in attaining new dimensions. To be productive, sugar companies have to work as sugar complexes, producing sugar, ethanol, power and other byproducts. Cogeneration of power in the sugar industry is an important source of revenue. The conditions in India demand sugar industries to generate and sell the electricity. This has created a new surge of interest among the sugar mills for surplus power generation during the crushing season using bagasse. This is possible and achievable only if the steam generation in the plant is increased and also the power and steam requirements of the plant are reduced. The study is aimed to relate various parameters of bagasse, cane crushed to steam generation. Single factor analysis of variance (ANOVA) is used to establish the significance of each parameter. Regression analysis is carried to establish the relation between parameters. The article arrives at a multiple regression equation relating the steam generated as a function of its associated parameters viz. cane crushed, bagasse % of cane, moisture % of bagasse, pol % of bagasse.

Keywords: bagasse, cogeneration, regression

INTRODUCTION

The sugar industry is attaining new dimensions in the fast changing world. It is poised to play a much higher and wider role. About 115 countries around the world produce sugar. Out of these, 67 countries produce from sugar cane, 39 from sugar beets and 9 countries from sugar cane as well as sugar beets. Looking to the present trend, it seems the cane-based sugar industry has a bright future [1].

The sugar industry is the largest agro-based industry located in the rural India. About 45 million sugar cane farmers, their dependents and a large mass of agricultural laborers are involved in sugar cane cultivation, harvesting and ancillary activities, constituting 7.5% of the rural population. There are about 0.5 million skilled and semi-skilled workers, mostly from the rural areas, engaged in the sugar industry [2]. The sugar industry in India has been a focal point for socio-economic development in the rural areas by mobilizing rural resources, generating employment and higher income, and developing transport and communication facilities.

Despite its large size and significant contribution to the rural economy of India, the sugar industry is in the web of complex problems namely;

- High stocks and low prices.
- Mounting cane arrears.
- Low competitive edge.
- Non-favorable Government policies.

To overcome this web of problems and to sustain itself over a longer period of time, the industry has to find methods to be competitive by producing byproducts, such as ethanol from molasses, power from bagasses.

Power is one of the most vital inputs for both economic and social development of the country. The Indian economy is on the threshold of growth, and vision and strategy in the domain of power sector assumes a greater importance. Being a prime mover of economic development, demand for electricity continues to grow relentlessly and new horizons have to be explored to fulfill it. Apart from wind and solar energy, the sugar industry has a potential source for generating renewable and environment friendly cogenerated power for supply to the grid. Ministry of Non-conventional Energy (MNES) announced policy guidelines to promote cogenerated power in Indian sugar mills.

Several studies carried out have established that significant potential exists in India for bagasse-based cogeneration. Further, the interest shown by the Government of India, the State Governments, and international funding agencies has provided the necessary thrust to encourage sugar mills to become more and more conscious of energy conservation and venture into the area of high-efficiency cogeneration leading to export of surplus power. As one of the largest processors of cane sugar, the Indian sugar industry is on the threshold of making a visible penetration in the power generation sector.

The sugar production process is energy-intensive, requiring both steam and electricity. Historically, sugar mills have been designed to meet their energy requirements by burning bagasses; this was seen as an economic means of producing electricity while cheaply disposing of bagasse. Over a period of time, the sugar companies are realizing a good amount of money by selling electricity to the grid.

Appropriate remuneration of electricity from bagasse cogeneration would increase the added value to the sugar sectors. This is especially valid because sugar-milling seasons often coincide with peak demand loads. In countries such as Brazil, where peak power can be up to ten times more costly than off-peak power, sugar mills can thus benefit immensely from the opportunity to sell electricity to the grid [3]. The long-term economic viability of sugar mills has become more vulnerable, mainly because of intense competition both in domestic and global sugar markets. The inherent energy inefficiency of design and operation, as well as the industry's high-energy requirements, is also a factor of growing importance.

To maximize the amount of electricity supplied to the grid, it is necessary to minimize the steam power to process, through the use of energy conservation techniques and management, as well as energy efficient equipment. In India, such policies have included conversion of mills from steam-driven to electricity-driven, use of steam saving equipment in boiler houses and energy-efficient pumps and motors [4] [5].

The surplus electricity production is influenced by factors like; bagasses % of cane, fiber % of cane, moisture % of bagasses, boiler efficiency, process steam consumption and electricity consumption in the mill. It appears that cane with a high fiber content, when burned in an efficient boiler, not necessarily at very high pressure, can achieve a satisfactory performance, in terms of surplus electricity. Typical figures from Mauritian cogeneration plants are used to benchmark the surplus electricity production for plants with low, medium and high-pressure boilers [6] [7]. Achievable targets ranged between 76 kWh/t cane to 143 kWh/t cane for the low and high pressure boilers, respectively for a factory without distillery. Efforts to improve production efficiency and economic viability in the sugar industry have traditionally focused on maximizing sugar cane yield per hectare of agricultural land and sugar produced per tonne of sugar cane grown. Although some cane co-products (such as bagasse and molasses) are utilized in this process, priority is accorded to sugar production. The traditional focus on sugar has made the industry vulnerable to changing market prices and weather patterns and prone to financial instability. There have been few attempts by sugar companies to consider all sugar cane resources as a bundle of potential products and services whose value could be maximized together. Co-production strategies present attractive options because they offer flexibility in producing varied quantities of sugar, ethanol and electricity depending on prevailing market conditions.

BAGASSE POWER: INDIAN POTENTIAL

Projections show that India has a potential for bagasse cogeneration ranging from 3.5 GW to 5.2 GW. This potential is expected to be tapped by 2012, resulting in annual savings of $923 million/year, while reducing annual CO_2 emissions by 38.7 million tones. Table 1 illustrates the potential, State by State, for producing exportable surpluses from sugar mill cogeneration. Figures are based on current mill numbers, capacities, efficiencies and cane availability, as well as future prospects in terms of modernization for optimization of exportable potential [6]. The potential is to be achieved mainly through improvements in energy efficiency and adoption of extra-high pressure (>60 kg/cm2) and temperature configurations. Despite adding to the mill's demand for steam and power, the corresponding increase in power output would in itself be so big as to make this worthwhile from a financial stance.

The bagasse has a gross calorific value of 19,250 KJ/kg at zero moisture content and 9,950 KJ/kg at 48% moisture content [8]. The net calorific value of bagasse at 48% moisture content is around 8,000 KJ/kg. The moisture content is the most crucial parameter in that, the lower the moisture contents, the higher the calorific value.

Table 1. State-wide Potential for Bagasse Cogeneration in India

State	*Potential (MW)*	*Commissioned exportable capacity*
Maharashtra	1,250	21.0
Uttar Pradesh	1,250	75.0
Tamil Nadu	500	105.0
Karnataka	500	125.0
Andhra Pradesh	300	49.3
Bihar	300	Nil
Gujarat	250	Nil
Punjab	150	Nil
Other	500	Nil
Total	5,000	375.9 (7.5%)

Source: MNES, New Delhi

COGENERATION TECHNOLOGY

Bagasse with 45% moisture content can be obtained from sugar factories with good milling processes. Poor milling performance results in bagasse with 52% moisture content. However, most mills produce bagasse with 50% moisture content in India. The bagasse is burned as a fuel in boilers to generate steam at high pressure and temperature. During combustion, the steam to bagasse ratio is normally taken as 2.2. Besides moisture, bagasse also contains fiber (which is of lingo-cellulosic nature), some sucrose (1-2%), and ash mainly in the form of silica, originating from soil and rocks brought in together with cane.

Bagasse, by virtue of its moisture content of around 50%, has a poor keeping quality in that it is prone to fermentation and associated chemical reactions that may lead to spontaneous combustion and hence fire outbreaks. At 30% moisture content, the keeping quality is improved, but energy is needed to dry it. Bagasse drying is generally not practiced in the sugar industry. Mill run bagasse has a bulk density of about 130-

150 kg/m^3 and hence poses storage problems in that it requires huge storage space and equipment for handling and is thus costly [4]. Hence, the objective is to burn as much of the bagasse as possible within a short period. Most factories have a bagasse reclaim system to cater to continuous mill operation. Anything in excess is kept in the open or under cover. This may be reclaimed and used during weekends or end-of-crop shutdowns to produce steam and electricity for internal use as well as for export to the grid.

Bagasse, as a combustible fuel for steam generation, is different from other commonly used fuels. Under such circumstances, the amount of air used is much higher than that used in other common fuels. This enables increased circulation resulting in more rapid evaporation of the moisture and enhancing combustion of the bagasse. Bagasse boilers are fitted with heat recovery equipment such as air pre-heaters and economizers to improve boiler efficiency [9].

Boiler efficiencies are normally computed on the basis of gross calorific value (GCV). However, it is not practicable to totally recover the latent heat from the water vapor in the flue gases in the case of bagasse, hence, the net calorific value (NCV) is used in such computation. Other losses such as radiation, air heating and incomplete combustion (in the form of fly ash) reduce the efficiency of the combustion. For example, ash-free dry bagasse has a GCV of 19,400 KJ/kg and the NCV is 18,000 KJ/kg. Excess air of 12% to 14% is normally required to ensure complete conversion of the carbon and hydrogen found in the bagasse into carbon dioxide and water with a minimum of carbon monoxide and unburned carbon.

In addition, the inherent energy inefficiency of design and operation as well as the industry's high-energy requirements is also a factor of growing importance. Considering all these factors, a case study was carried out at a sugar plant in the state of Karnataka (North).

The study is mainly aimed at understanding the impact of variation in bagasse % of cane, fiber % of cane, moisture % of bagasse, on steam generation. The study also aims at establishing the relationship between steam generated, bagasse % of cane, pol* % of bagasse, moisture % of bagasse, and cane crushed using regression analysis. These are the factors of the bagasse, which is the raw material for the steam generation.

*The apparent sucrose content of any substance expressed as a percentage by mass and determined by the single or direct polarization method. The term is used as if it were a real substance.

ANALYSIS AND RESULTS

Single factor analysis of variance (ANOVA) analysis

To measure the impact of the above mentioned factors on steam generation, a single factor ANOVA is carried out with the hypothesis that the factor groups will perform equally at 95% confidence level [10].

From the ANOVA Table 2, the significance value of F test is 0.333, so the hypothesis that groups perform equally is accepted. It is also justified by the means plot, shown in Figure 1. As the bagasse percentage of cane increases, the steam generated is also showing an increasing trend.

Table 2. ANOVA-Steam Generated and Bagasse % of Cane

	Sum of Squares	*df*	*Mean Square*	*F test*	*Sig.*
Between Groups	661,847.6	60	11,030.8	1.165	0.333
Within Groups	274,691.7	29	9,472.1		
Total	936,539.3	89			

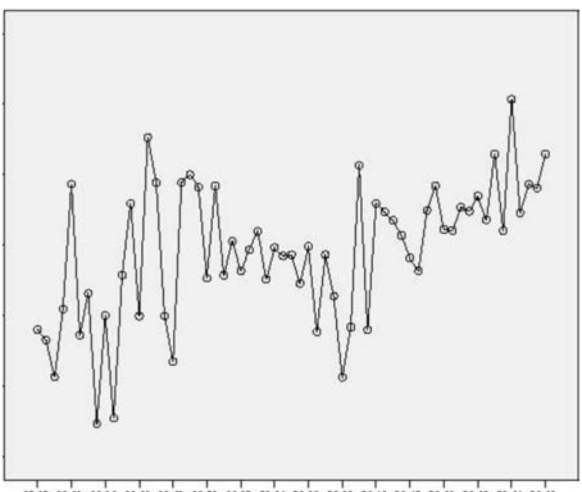

Figure 1. Means Plot of Steam Generated and Bagasse % Cane

The significance value of the F test in Table 3 for steam generated and moisture % of bagasse is 1.225, so the hypothesis that groups of moisture % of bagasse perform unequally is accepted. Now we know that groups differ in some way, we need to learn more about the structure of the differences. Figure 2 indicates that as the moisture % of bagasse increases, the steam generated is showing a decreasing trend.

Table 3. ANOVA- steam generated and moisture % of bagasse

	Sum of Squares	*df*	*Mean Square*	*F test*	*Sig.*
Between Groups	51,037.5	4	12,759.4	1.225	0.306
Within Groups	885,507.8	85	10,417.7		
Total	936,539.3	89			

The significance value of the F test for steam generated and fiber % of cane, as shown in Table 4 is 1.862, and the means plot, shown in Figure 3, indicates that as fiber percentage cane increases, the steam generated also increases.

Regression Analysis

Regression and correlation analysis shows us how to determine both the nature and strength of a relationship between variables [11]. Regression analysis is carried out to establish the relationship between

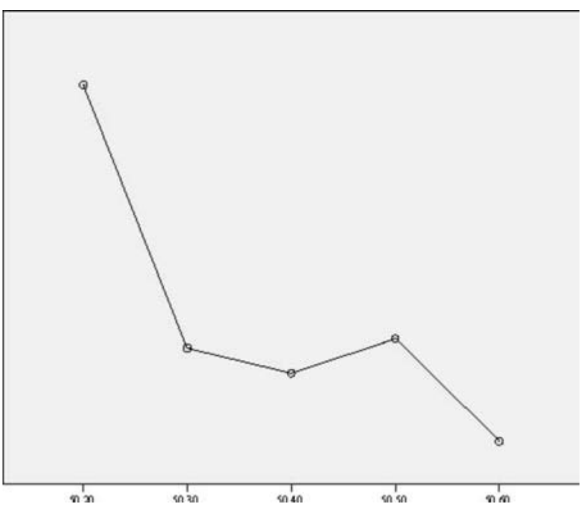

Figure 2. Means Plot of Steam Generated and Moisture % of Bagasse

Table 4. ANOVA-Steam Generated and Fiber % of Cane

	Sum of Squares	*df*	*Mean Square*	*F test*	*Sig.*
Between Groups	694,737.7	54	12,865.5	1.862	0.026
Within Groups	241,801.6	35	6,908.6		
Total	936,539.3	89			

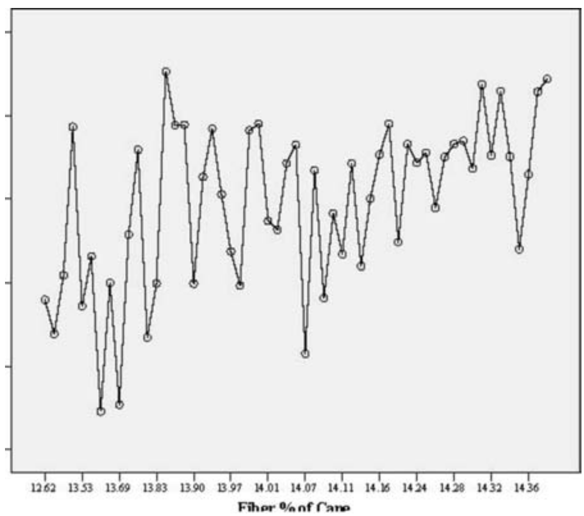

Figure 3. Means Plot of Steam Generated and Fibre % of Cane

the bagasse parameters and steam generated and also to establish the correlation.

The regression model summary, shown in Table 5, results give the overall goodness-of-fit as measures of R-square is 0.502, and correlation between actual and predicated value is 0.708. The standard error here refers to the estimated standard deviation of the error term. It is sometimes called the standard error of the regression.

Table 5. Regression Model Summary

Model	*R*	*R Square*	*Adjusted R Square*	*Standard Error of the Estimate*
1	0.708	0.502	0.472	74.51806

As shown in Table 6, the F value, 16.931, is highly significant indicating a linear relationship between the variables. Only an examination of the scatter plots of the variables can ensure us that the relationship is genuinely linear [12].

Total steam generated is predicted from the coefficients shown in Table 7. The equation for prediction is:

$$Y = 5967.247 + 0.212*X_1 + 35.301* X_2 - 117.840 * X_3 + 63.152 * X_4$$

where;

Y = Total steam generated
X_1 = Cane crushed
X_2 = Bagasse % of cane
X_3 = Moisture % of bagasse
X_4 = Pol % of bagasse.

Table 6. Regression Model ANOVA

Model		*Sum of Squares*	*df*	*Mean Square*	*F test*	*Sig.*
1	Regression	470,092.2	5	94,018.4	16.931	0.000
	Residual	466,447.1	84	5,552.9		
	Total	936,539.3	89			

The column in Table 7 headed Beta gives us more information about the relative importance of the variables. Beta contains standardized coefficients. A change of one standard deviation of moisture % of bagasse will produce a change -0.109 standard deviation in total steam production. A change of one standard deviation in bagasse % of cane will produce a change of 0.238 standard deviation in total steam production.

The histogram of the standardized residuals in the Figure 4 represents frequency (with bars), while the superimposed curve represents the ideal normal distribution of the residuals. The normal probability plot (Figure 5) of standardized residuals shows that most of the points lie on diagonal and closer to the diagonal, indicate that the residuals are normally distributed.

Table 7. Regression Coefficients

Model	Un-standardized Coefficients B	Un-standardized Coefficients Standard Error	Standardized Coefficients Beta	T-Test	Sig.
(Constant)	5,967.2	4193.91		1.423	0.158
Can Crished	0.212	0.031	0.564	6.904	0.000
Bagasse % of Cane	35.30	12.93	0.238	2.731	0.008
Moisture % of Bagasse	-117.84	82.76	-0.109	-1.424	0.158
Pol % of Bagasse	63.15	103.54	0.051	0.610	0.544

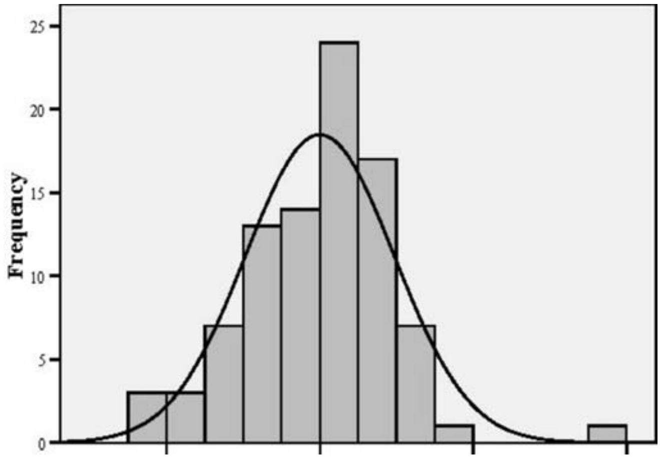

Figure 4. Histogram

The regression standardized residual plot Figure 6 will also indicate the same pattern as that of the histogram. Figure 7, the partial regression plots of moisture % of bagasse and bagasse % of cane, indicates the same patterns but only one residual lying on the opposite side. While the cane crushed indicates a linear increase as that of normal probability plot, the spread appears to be equal on either side.

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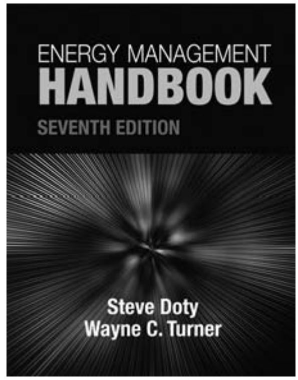

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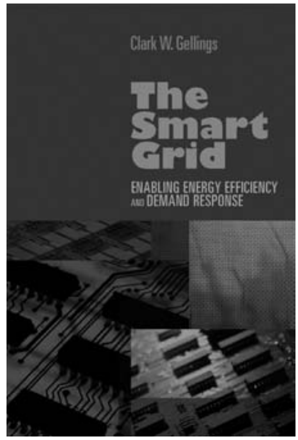

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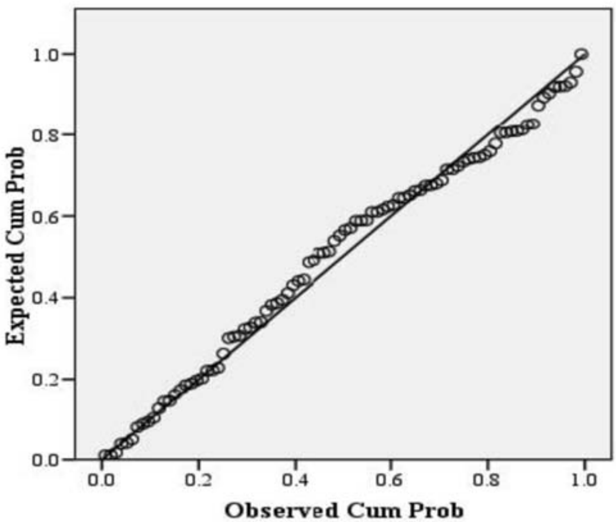

Figure 5. Normal P-P Plot of Regression Standardized

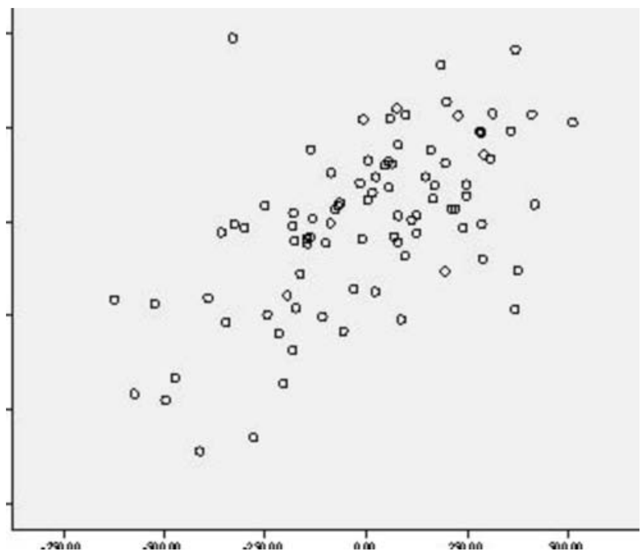

Figure 6. Regression Standardized Residual Plot

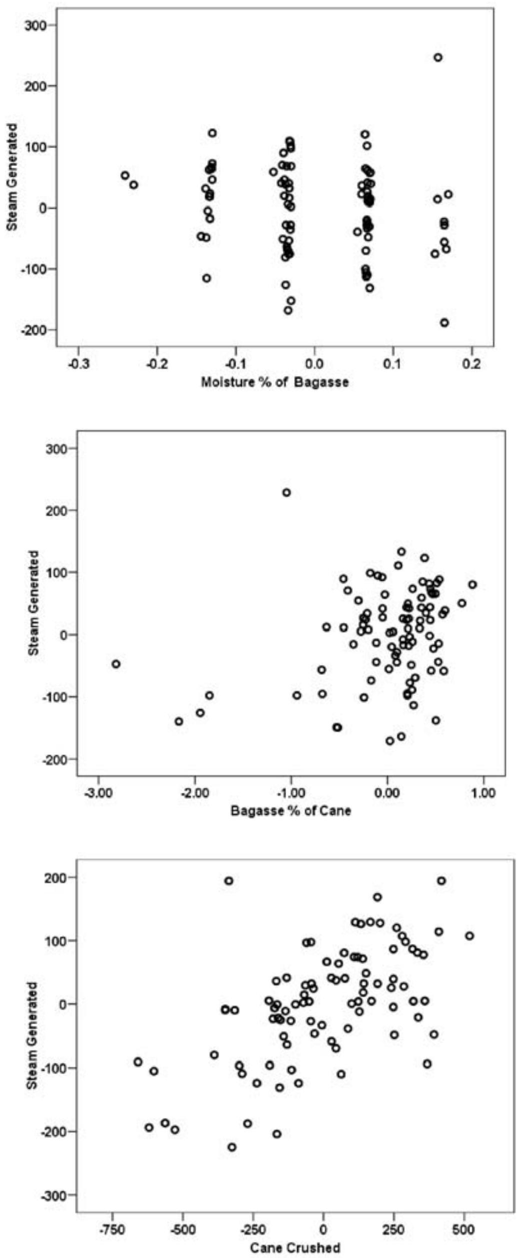

Figure 7. Partial Regression Plots of Moisture % Bagasse, Bagasse % Cane, and Cane Crushed

CONCLUSION

The article gives an overview of the importance of the sugar industry to the Indian economy and the issues faced by them. It emphasized the importance of bagasse-based cogeneration in India and its potential in the Indian context. Generation of exportable electricity from bagasse in sugar mills is universally accepted as desirable, economic, and environment friendly, and the potential of this electricity source is substantial. Several parameters, including bagasse parameters, affect the process of cogeneration. The article demonstrates the impact of variation in bagasse % of cane, fiber % of cane, the moisture % of bagasse on steam generation. The developed statistical model relates the steam generation with bagasse parameters. The article arrives at a multiple regression equation relating the steam generated as a function of its associated parameters viz. cane crushed, bagasse % of cane, bagasse % of cane, moisture % of bagasse, and pol % of bagasse. The regression analysis indicates that bagasse % of cane is a major parameter impacting the total steam generation and, in turn, the power. The ANOVA analysis indicates that as bagasse % of cane increases, the steam generated will increase and also it reveals that increases in moisture % will reduce steam generated.

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