Bagasse is usually combusted in boilers to generate steam for downstream processes. The utilisation of bagasse waste is essential to economic production of sugar. Co-generation and grid connection would certainly be of much help in Zimbabwe if stronger linkages exist between sugar companies and the utility company. Such linkages have been found to work in Mauritius where 10 out of 11 sugar factories are exporting electricity during the crop season [1].

Electrical energy supplied by Zimbabwe’s power stations has been found to be about 7090 GWh per annum, approximately 65% of the country’s annual demand, (12 500 GWh). The balance is supplied by imports [2]. If the two sugar factories (Triangle Limited and Hippo Valley Estates) were to feed into the grid, the deficit may be reduced.

**Bagasse production and use at Hippo Valley Estates**

This research project was carried out to assess the use of bagasse in co-generation at HVE, as well as to provide the company and other sugar manufacturing companies with economic knowledge on bagasse based co-generation. HVE has been co-generating steam and electricity for their site specific consumption since the company started operating in 1959. The company currently processes 2,33 Mt of sugar cane annually to get 270 000 t of sugar.

Electrical production is a possible source of revenue the company could exploit using its excess electrical generating capacity using excess fuel (bagasse), which is currently incinerated inefficiently. The quantity of bagasse produced was found to average 27,5% by weight of cane crushed implying that 275 kg of bagasse was produced per ton of sugar cane. HVE produces 640 750 t of bagasse annually, from which it generates 13,5 MW of electricity for each crushing period. There is potential to double the generation capacity.

**Technological description of the plant at HVE**

The power plant is driven by steam, produced by both bagasse and coal fired boilers. There are six high pressure (3,1 MPa) John Thompson water tube type boilers in use. Their final steam temperature is 400°C and Table 1 gives the description of the boilers.

<table>
<thead>
<tr>
<th>Boiler no.</th>
<th>Fuel type</th>
<th>Steam temperature (°C)</th>
<th>Pressure (MPa)</th>
<th>Max. continuous rating (t/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Coal and bagasse</td>
<td>400</td>
<td>3,1</td>
<td>45</td>
</tr>
<tr>
<td>2</td>
<td>Coal and bagasse</td>
<td>400</td>
<td>3,1</td>
<td>45</td>
</tr>
<tr>
<td>3</td>
<td>Coal and bagasse</td>
<td>400</td>
<td>3,1</td>
<td>45</td>
</tr>
<tr>
<td>4</td>
<td>Bagasse</td>
<td>400</td>
<td>3,1</td>
<td>100</td>
</tr>
<tr>
<td>5</td>
<td>Bagasse</td>
<td>400</td>
<td>3,1</td>
<td>68</td>
</tr>
<tr>
<td>6</td>
<td>Bagasse</td>
<td>400</td>
<td>3,1</td>
<td>68</td>
</tr>
</tbody>
</table>

Table 1: John Thompson boilers at HVE fuelled by coal and bagasse.

If all boilers operate at maximum continuous rating their output would be 371 t/hr of steam. They currently generate 200,45 t/hr, which implies that they operate at 54% capacity. Boiler 1, 2 and 3 have a combined rating of 135 ton/hr and they produce 70,1 t/hr implying that they are operating at 52% capacity. Boilers 4, 5 and 6 have a combined rating of 236 t/hr steam production but they produce 130,35 t/hr, which implies that they were operating at 55% capacity. The first three boilers have a travelling grate for dumping ash after the fuel has been burnt. Boilers 4, 5, and 6 are fuelled by bagasse and these boilers have dump grates.

**Methodology**

The daily plant reports, which contain quantitative data, were chosen as the main tool of data collection. Reports for the months of July and August were analysed and then only days which had crushing rates of more than 10 000 t of sugar cane were sampled. Records for the steam production, steam temperature, rate of steam flow from the boilers, power generation as well as steam supply to the process departments were collected. The data collected was then used to determine the average steam produced per day on an hourly basis.
Steam consumption by steam turbines

The steam consumption of the steam turbines was determined as follows:

\[ Q = \frac{860}{(\lambda - \lambda^1) \cdot \mu \rho_m \rho_r \rho_g} \]  

(1)

\[ Q = \text{Steam consumption of the turbo – alternator set, in kg/kWh} \]

\[ \lambda = \text{total heat of the steam at the nozzle chest, in kcal/kg} \]

\[ \lambda^1 = \text{total heat of the exhaust steam, in kcal/kg} \]

\[ \eta = \text{thermodynamic efficiency of the turbine} \]

\[ \rho_m = \text{mechanical efficiency of the turbine} \]

\[ \rho_r = \text{efficiency of the reduction gear} \]

\[ \rho_g = \text{efficiency of the generator or alternator} \]

\[ \rho_g \text{ varies with power 0.94 – 0.985,} \]

\[ \rho_r \text{ varies from 0.97 – 0.985,} \]

\[ \eta \text{ thermodynamic efficiency of the turbine [3], depends on:} \]

- The mechanical standard of construction
- Its power; the more powerful the turbine the higher the efficiency
- The adiabatic heat drop; the higher the drop the better the efficiency [4]

The steam consumption losses through condensation and losses by leaks were determined from the following relationships:

- Losses through condensation range, which is 3 – 5%
- Losses by leaks range, which is 2 – 3%

The data used to calculate the steam consumption rate of the steam turbines is presented in Table 3.

Analysis of bagasse and coal used

Bagasse

The ultimate analysis as well as the proximate analysis of bagasse was undertaken. The proximate analysis defines the magnitude of the ash, moisture, volatiles and fixed carbon, while the ultimate analysis defines the composition of carbon, hydrogen, nitrogen, oxygen and sulphur. The Gross Calorific Value (GCV) and Net Calorific Value (NCV) on wet basis were determined using the following equations:

\[ \text{GCV}_w = 4600(1 - W) - 1200S \]  

(2)

\[ \text{NCV}_w = 4250 - 485W - 1200S \]

where W is the water content in bagasse (48%) and S is the sugar content in bagasse (4%) [3].

The quantity of heat remaining to be transferred to the steam is therefore given as:

\[ M_s = (4250 - 485W - 1200S - q) \cdot a \beta \eta \]

(4)

\[ = (\text{NCV}_w - q) \cdot a \beta \eta \]

(5)

The coefficients are \( a, \beta, \eta \) where \( a \) is the coefficient taking into account the losses due to incomplete combustion, \( \beta \) is the coefficient taking into account the losses due to radiation and \( \eta \) is the coefficient taking into account the losses due to unburnt solids. \( M_s \) is the heat transferred to the steam per kg of bagasse burned in \( \text{kJ/kg} \), \( W \) is moisture of bagasse, \( S \) is the sugar content per kilogram of bagasse and \( q \) is the sensible heat loss of flue gases. \( q = 0.98 \) for ordinary furnaces and 0.975 for Spreader stoker furnaces [3], the type of furnaces in use at HVE, \( S = 0.975 \) and \( W = 0.965 \). The sensible heat loss \( q \) was found to be 1.43 M\( \text{J/kg} \). The sensible heat loss was determined as follows:

\[ q = [(1 - W)(1.4m - 0.13) + 0.5] \cdot t \]

(6)

Where \( q \) is the sensible heat loss in \( \text{kJ/kg} \), \( W \) is the moisture content in the bagasse (48%), \( m \) is the excess air ratio (1.4) and \( t \) is the flue gas temperature (235°C).

The quantity of heat transferred to the steam, \( M_s \), was found to be 5.89 M\( \text{J/kg} \). The boilers produced steam at 3,1 Mpa. At this pressure the corresponding enthalpy (h) was found to be 3,23 M\( \text{J/kg} \). Boiler feed-water was supplied at 90°C implying a feed-water enthalpy \( (h_f) \) of 0,377 M\( \text{J/kg} \). The difference between the two gave the heat added to water (2,85 M\( \text{J/kg} \)). 1 kg of steam requires 2,85 M\( \text{J} \) from the bagasse heat added to water (2,85 M\( \text{J/kg} \)). 1 kg of bagasse can produce 6,28 MJ of energy.

\[ \alpha = \frac{5.89}{2.85} = 2.07 kg \]

(7)

Economic evaluation

Different frameworks and methods of pricing by co generating companies are available and these can be adopted by sugar manufacturing companies.

Pricing of power sales by co-generators

There are several types of power transactions that can arise in the context of a market for excess power supply from the co-generators. The following transactions can be followed out or used:

- Direct sale to the grid: In this transaction a co-generating sugar mill will sell its excess power to the utility company for example, ZESA. The selling price would be a contractually agreed price.
- Wheeling: In this transaction the utility company will transmit (wheel) the co-generated power for delivery to another location. The utility company changes a transmission (wheeling) fee. The final purchaser of electricity pays the sugar mill directly for the power at the agreed price.
- Banking: This transaction involves a co-generator selling its excess power to ZESA for withdrawal for its use at a later time.
- Banking plus wheeling: In this transaction a utility company pays back the banked energy by wheeling the power to a delivery point different from the point of injection.

Power purchase tariffs for direct sales to the grid are the ones of concern. This method comprises over 99% of transactions in established power markets worldwide. The economic cost of generating and supplying electricity and therefore the value to the grid of any purchases vary by time of the day due to demand variations.

Avoided cost

The value of power generated by independent power producers (IPPs) is given by a utility company as the avoided cost to the utility. These are the costs of generation, transmission and distribution, as well as fuel, which the utility company (ZESA) no longer needs to incur by virtue of the operation of the independent source. The avoided energy cost is usually given to the utility company. However this cost has to be compared to the generation cost of a company.

Power generation cost

No-cost waste product is used as a fuel and co-generation requires little or no additional labour at the mill. A large element of the cost of co-generation involves the initial capital investment. The economic viability is highly sensitive to the amount of power exported per unit of capital investment.

Capital & operating cost estimates

A 20 MW pass-out steam turbine purchased in 2001 cost $5,2-million. The cost of piping, civil, electrical, foundation work, building, water cooling, and instrumentation were taken from actual projects elsewhere for a similar cost.
size of steam turbine [5]. The total estimated capital costs included 20% for miscellaneous items and for contingency.

In an economy with market annual interest rate of \( i \) and an average annual inflation \( f \), the discount rate is given by the following:

\[
r = \frac{[1 - (1 + i)^n]}{[1 - (1 + f)^n] - 1}
\]

(8)

It can be observed that the real discount rate is therefore not \( i \) [6]. The discount rate used in all the economic analysis in this study will be assumed using the United States of America market interest rate (\( i \)), which is 6.75% and inflation rate (\( f \)), which is 3.2%. For the analysis, the uniform series present worth was used and is given in [7].

\[
P/A(i, n) = \frac{A(1 + i)^n - 1}{[1 + (1 + i)^n]}
\]

(9)

Where \( P/A \) is the present worth of the investment, \( i \) is the interests and \( n \) is the number of years.

Table 4 shows the capital and operating estimates used to determine the costs applied during the determination of the net present value of the investment as well as the payback period.

Results and discussion

Ultimate and proximate analysis of bagasse and coal

Table 5 shows the proximate and ultimate analysis of bagasse. The moisture content of the bagasse was found to be 48% and the GCV was found to be 9.81 MJ/kg while the NCV was found to be 7.85 MJ/kg. However, it was found that not all of this heat from the bagasse goes into steam production. There are also heat losses taking place in the furnace as well as in the boiler. The losses consist of the following:

- Latent heat of water formed by combustion of hydrogen found in the bagasse
- Latent heat of water contained in the bagasse
- Sensible heat of the flue gas leaving the boiler
- Losses of heat in ash and grit
- Losses of heat by radiation and convection from the furnace and boiler

\[
\text{Nett calorific value} = 9.81 \text{ MJ/kg}
\]

Table 5: Proximate and ultimate analysis of bagasse.

<table>
<thead>
<tr>
<th>Ultimate analysis</th>
<th>Composition (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon</td>
<td>49.2</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>4.69</td>
</tr>
<tr>
<td>Oxygen</td>
<td>43</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>0.18</td>
</tr>
<tr>
<td>Sulphur</td>
<td>0.02</td>
</tr>
<tr>
<td>Other elements</td>
<td>2.43</td>
</tr>
</tbody>
</table>

Table 6: The ultimate and proximate analysis of coal.

<table>
<thead>
<tr>
<th>Proximate analysis</th>
<th>Composition (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fixed carbon</td>
<td>11.82</td>
</tr>
<tr>
<td>Volatile matter</td>
<td>84.79</td>
</tr>
<tr>
<td>Ash</td>
<td>2.91</td>
</tr>
<tr>
<td>Moisture</td>
<td>48</td>
</tr>
<tr>
<td>Total</td>
<td>100</td>
</tr>
</tbody>
</table>

Table 5: Proximate and ultimate analysis of bagasse.

- Losses due to incomplete combustion of carbon giving carbon monoxide instead of carbon dioxide

The 7.85 MJ/kg already takes into consideration the losses due to the first and second points. The other losses are taken into account by means of coefficients applied to the total quantity of heat, 9.81 MJ/kg. Table 6 shows the ultimate and proximate analysis of coal. The NCV for coal was found to be 23.04 MJ/kg and the total sensible heat loss was found to be 2.15 MJ/kg resulting in 21.07 MJ/kg of the heat transferred to steam.

Bagasse and steam production

The average steam produced per day was found to be 193.11 tons/hr. On average, the excess bagasse stored in the bagasse store was found to be 470 t/day and the crushing rate of cane averaged 10836 t/day. There are six steam turbines sets at HVE but during the investigations only two were in operation – these were STG6 rated at 20 MW and STG2 rated at 5 MW. STG2 could do both pass-out or condensing. The two could meet the plant and the estate’s electrical requirements, which was 13.5 MW.

Table 7 presents the steam consumption rates by steam turbines. The steam consumption by prime movers, which are shredders, de-watering mills, drying off mills and steam feed pumps was found to be 77.53 t/hr. The total steam requirement for the plant was therefore 200.43 t/hr. Table 8 shows the excess steam and excess bagasse produced. The bagasse used was found to be 130.30 t/hr and this quantity of bagasse was capable of producing 267.92 t/hr of steam. This implied an excess steam of 69.3 t/hr that could be produced. The total average hourly bagasse storage was found to be 18.86 tons, and adding this to hourly stored bagasse resulted in an excess storage capacity of 52.33 t/hr. Since there are 244 days for crushing cane per year, the excess bagasse was 306 444 t/year and this could be used to generate excess electricity, potentially 69510.72 MWh per year.
The steam consumption rate was found to be 8.67 kg/kWh without considering heat loss. Adding heat loss of 5%, steam consumption rate was found to be 9.104 kg/kWh. Considering STG6, which produces 11 MW at steam consumption rate of 100, 144 t/hr, then excess steam of 69.3 t/hr, would be capable of producing excess power of 7.61 MW. It has been established that 1 kg of bagasse produces 2.064 kg of steam, and bagasse stored was 18.86 t/hr, implying a potential of 38.93 t/hr available steam, which could be used to generate 4.26 MW of electricity. Using bagasse alone the potential power output from the plant could total 25.37 MW and the company could sell an excess of 11.87 MW. The maximum capacity of the company was found to be 33 MW. At 25.37 MW the plant could be operating at 75% capacity.

Economic evaluation

The discount rate was found to be 3.44%. A revenue of Z$3.06/kWh (0.056 $/kWh in 2002) was used, being the domestic tariff charge from ZESA for a customer using electricity in the range of 51 – 300 kWh and this happened to give the least expected price [8]. Mangwengwende [2] also averaged the electricity tariff at 4.9 $c/kWh and this was within the range used for the economic calculations.

The NPV of the investment indicated feasibility. The cost to the company per kWh generated was found to be $0.0151 and the payback period was found to be 3.3 years. The sensitivity analysis of the investment was undertaken and the results showed that the project was sensitive to price changes as well as to energy output changes.

Conclusion and recommendations

It was established that 69.3 t/hr of steam was lost either through inefficient burning of bagasse or through venting off of steam through valves on the boilers or through the main range. It was also established that if inefficient use of bagasse and venting of steam is stopped this would imply a realisation of power equivalent to 7.61 MW.

The plant was found to operate under conditions where excess bagasse caused operational problems of storage and handling and as a result bagasse was burnt inefficiently. If steam turbines were to be operated optimally then the bagasse that is stored on a daily basis could be used to produce extra power of 4.26 MW. The resulting possible power output was found to be 11.87 MW. This translated to 69 510.72 MWh per year. The company was found to be able to collect revenue of about $3.9-million per year from the utility company ZESA. For profitable co-generation the price greater than a generation cost of $0.0151/kWh was recommended.

Table 7: Steam consumption by steam turbines.

<table>
<thead>
<tr>
<th>Type of turbine</th>
<th>Rated power (MW)</th>
<th>Rated steam consumption (tons/hr)</th>
<th>Actual power output (MW)</th>
<th>Steam consumption (tons/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>STG2 Pass out/condensing</td>
<td>5.00</td>
<td>45.52</td>
<td>2.50</td>
<td>22.76</td>
</tr>
<tr>
<td>STG5 Pass out</td>
<td>8.00</td>
<td>72.83</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>STG6 Pass out</td>
<td>20.00</td>
<td>182.08</td>
<td>11.00</td>
<td>100.14</td>
</tr>
<tr>
<td>Total</td>
<td>33.00</td>
<td>300.43</td>
<td>13.5</td>
<td>122.90</td>
</tr>
</tbody>
</table>

Table 8: Excess bagasse and steam (tons/hr).

<table>
<thead>
<tr>
<th>Bagasse used</th>
<th>Steam production</th>
<th>Steam consumption</th>
<th>Excess steam</th>
<th>Excess bagasse</th>
<th>Excess stored bagasse</th>
</tr>
</thead>
<tbody>
<tr>
<td>130.30</td>
<td>267.92</td>
<td>200.43</td>
<td>69.3</td>
<td>33.47</td>
<td>52.33</td>
</tr>
</tbody>
</table>

References


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