Simulations of steam balances were carried out for two cane throughputs (150 TCH and 275 TCH) for various fiber % cane values in the range of 11 to 18% and for various imbibitions % fiber values (150 to 350) to determine the amount of electricity that could be exported for each scenario. A regression equation was established relating pol % bagasse and imbibition % fiber. The combined income from sale of surplus electricity and additional sugar extracted was calculated and plotted against fiber % cane for each imbibition rate and for each throughput. This simulation indicated that under the conditions of thermal efficiency which had been assumed, there would be a financial advantage in operating the factory at a lower imbibition rate for fiber % cane values higher than 14%. However, at a given fiber % cane below 14%, it would be more profitable to increase the imbibition rate. A regression equation was developed to relate the pol to an imbibition % fiber. This equation was used to construct the isocost chart. For each throughput, the annual return on investment was calculated, and the optimum imbibition rate was determined.

**Key words**: Bagasse, electricity, optimization.
Assumptions

The following assumptions have been made. They apply to conditions in Mauritius.

- Factory capacities: 150 and 275 TCH (tons cane per h) (TCH)
- Fiber % cane: 11 to 18 (varied by unit increments)
- Imbibition % fiber: 150 to 350 (varied by increments of 50)
- Extraction equipment: 2 cane knives, 1 shredder, 4 mills
- Juice heating: 2 stages with liming at 70°C
- Live steam: 6000 kPa abs, 505°C
- Exhaust steam: 200 kPa abs, saturated
- Total power required by factory: 30 kw/TCH @ 14% fiber

Further details appear in Appendix I.

Power requirements of factory

At 150 TCH and 14% fiber, the total power required by the factory would be 4500 kW, while the energy required for cane preparation (40 kW/TFH) and milling (60 kW/TFH) would total 2100 kW for processing and services. It can be assumed that the power required for processing and services is independent of the fiber content of cane and the power available for electricity sale is therefore directly proportional to the fiber content of the cane at a given thermal efficiency.

Simulations have been carried out to determine the exhaust steam demand, the high pressure (HP) steam demand and HP let down to exhaust.

Figure 1 shows the variations in HP let down for various fiber % cane values at a constant imbibition rate (275%F) for the two throughputs. For each throughput, one curve is based on the use of exhaust steam (EXH) in the pans and the other on the use of first effect vapor (V1). The let down can be done through a pass-out condensing turbo alternator and used to produce electricity. The surplus high-pressure steam can be used to produce electricity by means of the condensing turbine.

The effect of imbibition rate

An increase in imbibition rate normally decreases the pol % bagasse in the 150 to 350 imbibition % fiber range, but also increases the steam requirement of the factory and should therefore reduce the energy available for electricity generation. An attempt has been made to relate pol % bagasse to imbibition % fiber for four milling units tandems in Mauritius using weekly data for the 1990 crop
FIGURE 1. High pressure steam let-down to exhaust for imbibition % fiber of 275.
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(Figure 2). The correlation coefficient (0.64), is low and experimental work has been planned for a more accurate investigation of the relationship. On the basis of available data and its regression equation, the increase in income from sugar to the factory as a result of the lower pol in bagasse with a higher imbibition has been calculated as shown in Appendix II.

Income from sugar and sale of electricity

An increase in imbibition rate increases income from sugar and decreases the proceeds from the sale of electricity. By adding the income from both sources and plotting total net income against fiber % cane and imbibition % fiber, it is possible to find the most profitable combination of the two sources of income (Figure 3 and 4). In plotting the curves the base line has been assumed for 13 fiber % and 275 imbibition % fiber, typical figures for Mauritian factories where a relatively small proportion of total energy generated is sold to the grid. The rate for electricity purchase varies with the amount supplied (Table 1).

**TABLE 1. Rates for purchase of electricity.**

<table>
<thead>
<tr>
<th>GWh</th>
<th>Purchase price</th>
</tr>
</thead>
<tbody>
<tr>
<td>Up to 30 GWh</td>
<td>0 Rs 78.3 cs*</td>
</tr>
<tr>
<td>&gt; 30 GWh and &lt; 35 GWh</td>
<td>0 Rs 88.3 cs</td>
</tr>
<tr>
<td>&gt; 35 GWh</td>
<td>0 Rs 98.3 cs</td>
</tr>
</tbody>
</table>

* 1 US $ = Rs. 16.90, 1Rs = 100 cs.

Calculations of income from sale of electricity over the datum line are given in Appendix III where it is assumed that a crop season lasts for 2,500 h so that to produce 30 GWh, the factory has to generate 12,000 kW continuously. The purchase price of electricity increases as the supply increases and therefore favors the high fiber, low imbibition scenario.

**DISCUSSION**

The effect of fiber % cane on additional income from sale of sugar as a result of higher imbibition is shown in Figure 5 (150 TCH). The curves indicate that, at the same imbibition, income decreases with an increase in fiber content and is proportional to imbibition % fiber. These results are not surprising, but they are useful because they provide a cost justification for a well known trend. They also show that an increase in capacity from 150 TCH to 275 TCH (Figure 6) does not affect income per ton of cane.
FIGURE 3. Combined income from sale of surplus electricity and additional sugar extracted for a cane crushing rate of 150 TCH.
FIGURE 4. Combined income from sale of surplus electricity and additional sugar extracted for a cane crushing rate of 275 TCH.
FIGURE 5. Income from additional sugar extracted for a cane crushing rate of 150 TCH.
FIGURE 6. Income from additional sugar extracted for a cane crushing rate of 275 TCH.
Figures 7 and 8 show the effect of fiber % cane and imbibition % cane on income from sale of electricity for the two crushing rates. They confirm that income from electricity increases with fiber % cane and decreases with imbibition % fiber. Again, the income is directly proportional to cane throughput.

The combined income from sale of surplus electricity and additional sugar extracted has been plotted against fiber % cane for 150 TCH (Fig. 3) and 275 TCH (Figure 4). At the lower crushing rate the changes in imbibition rate has no practical effect on income in the range 14 to 17 fiber %, and the effect of imbibition variations only become noticeable at low fiber (11% to 13%) when there is a relatively small amount of surplus electricity for sale. At the higher crushing rate (275 TCH) there is an increase in net income with higher fiber % cane values and the rate of imbibition also influences results because of the higher unit rate for electricity purchase at higher levels of electricity production.

This simulation indicates that under the conditions of thermal efficiency which have been assumed, there would be a financial advantage in operating the factory at a lower imbibition rate for fiber cane values higher than 14%. However, at a given fiber % cane below 14% it would be more profitable to increase the imbibition rate. It must be stressed that the relative costs of sugar and electricity and the thermal efficiency of the factory can modify these conclusions and that this study should only be used as model for each factory to calculate its own optimum operating conditions, taking into consideration the investment cost required.

ACKNOWLEDGMENTS

The authors wish to acknowledge the assistance given by S. Tse Chi Shum, A. Ragen and S. Sakurdeep of the Technology Division of the Mauritius Sugar Industry Research Institute in running the simulation programs and preparing the graphs.

REFERENCES

4. SMRI Steam programme. Personal communication.
FIGURE 8. Income from sale of surplus electricity for a cane crushing rate of 275 TCH.
APPENDIX I

Assumed data

5 evaporation effect
2 boiling system
1 pass out condensing turbo alternator

| Heat losses on the evaporator | 3% |
| Heat losses on the pan floor  | 3% |
| Brix % cane                  | 15 |
| Brix of bagasse              | 2  |
| Moisture % bagasse           | 50%|
| Ash % bagasse                | 1  |
| Suspended solids in mixed juice | 1 |
| Bagacillo % mixed juice      | 0.5|
| Filtrate % mixed juice       | 10 |
| Brix % filter cake           | 1.5|
| Moisture % filter cake       | 80 |

Vapor 1: 156 kPa abs, saturated (V1)
Vapor 2: 122 kPa abs, saturated (V2)
Vapor 3: 89 kPa abs, saturated
Vapor 4: 57 kPa abs, saturated
Vapor 5: 15 kPa abs, saturated

<table>
<thead>
<tr>
<th>Vapor source</th>
<th>Temperature (°C)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>in</td>
<td>out</td>
</tr>
<tr>
<td>Mixed juice heater 1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mixed juice heater 2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Clarified juice heater</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Exhaust</td>
<td>97</td>
<td>107</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Vapor source</th>
<th>Brix syrup</th>
<th>Brix massecuite</th>
<th>Massecuite m³/t Brix</th>
</tr>
</thead>
<tbody>
<tr>
<td>A pan boiling</td>
<td>V1</td>
<td>60</td>
<td>92</td>
</tr>
<tr>
<td>C pan boiling</td>
<td>Exhaust</td>
<td>70</td>
<td>95</td>
</tr>
</tbody>
</table>

Pan water % vap Iig steam % vap

<table>
<thead>
<tr>
<th>Pan</th>
<th>Iig steam % vap</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>8.0</td>
</tr>
<tr>
<td>C</td>
<td>8.0</td>
</tr>
<tr>
<td>Exhaust steam sundries</td>
<td>2.0 t/h</td>
</tr>
</tbody>
</table>

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Electrical power for process services: 2400 kW for 150 TCH
Electrical power for process services: 4400 kW for 275 TCH
Feed water temperature: 80°C
Boiler efficiency: 80%
Loss of bagasse: 5%
High pressure steam sundries: 1 t/h
% high pressure steam losses: 2.0
Exhaust steam losses: 1%

Turbine efficiency
(%)

APPENDIX II

Calculation of income through pol gain in bagasse

Cane crushing rate = 275 TCH
Datum: Fiber % cane = 13
Imbibition % fiber = 275

Regression equation relating pol % bagasse and imbibition % fiber is given by:
y = 2.32526 - 0.0022041 x ; r = 0.64
where, y = Pol % bagasse.
x = Imbibition % fiber.

therefore, Pol % bagasse @ imbibition % fiber of 275 = 1.72
Pol % bagasse @ imbibition % fiber of 300 = 1.66

Fiber % cane = 13
Moisture % bagasse = 50
Brix in bagasse = 2

to therefore, Fiber % bagasse = (100–50–2) = 48

Wt of fiber @ fiber % cane of 13 = \( \frac{13}{100} \times 275 \) = 35.75 t/ha
Wt of bagasse @ fiber % cane of 13 = \( \frac{100}{48} \times 35.75 \) = 74.48 t/ha
Wt of fiber @ fiber % cane of 18 = \( \frac{18}{100} \times 275 \) = 49.50 t/ha
Wt of bagasse @ fiber % cane of 18 = \( \frac{100}{48} \times 49.5 \) = 103.125 t/ha

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Therefore, loss of sugar in bagasse @ fiber % cane of 18 and imbibition %
fiber of 300 relative to datum = \( \frac{(1.66 \times 103.15) - (1.72 \times 74.48)}{100} \) = 0.431 t/ha

Purity of last expressed juice = 75
Purity of molasses = 35
Purity of sugar = 99
SJM recovery = \( \frac{99 (75-35) \times 100}{75(99-35)} \) = 82.5

B.H.E. = 99
B.H.R. = \( \frac{82.5 \times 99}{100} \) = 81.675
Pol of sugar = 98.5
Sugar loss per h in bagasse = \( \frac{(0.431 \times 100)}{98.5} \) = 0.357 t/ha

Price of sugar per ton = Rs. 6,603.66/t (1 US $ = Rs. 16.90)
1 Rs = 100 cs
therefore, loss in income/hr = Rs. (0.357 \times 6,603.66) = Rs. 2,357.51

**APPENDIX III**

Calculation of income from electricity

Cane crushing rate = 275 t/ha

Datum: Fiber % cane = 13
Imbibition % fiber = 300
From simulation, electricity produced per h = 12,200 kWh

If fiber % cane = 13
and imbibition % fiber = 300
then, from simulation, electricity produced per h = 11,922 kWh

Assuming a crop season of 2,500 h, the rates for purchase of electricity from Table 1 can be converted into:

up to 12,000 kW for each 1 kWh 78.3 cs (1 US $ = Rs. 16.90)
> 12,000 kW and < 14,000 kW for each 1 kWh 88.3 cs (1 Rs. = 100 cs)
> 14,000 kW for each 1 kWh 98.3 cs
therefore, the rate for purchase of electricity per kWh are:

1) For electricity between 11,922 and 12,000 kWh = 78.3
2) For electricity between 12,000 and 12,200 kWh = 88.3

therefore, shortage in income over datum = (12,000–11,922) × 78.3
+ (12,200 – 12,000) × 88.3
= Rs. 237.67

If fiber % cane = 18
and imbibition % fiber = 300
then, from simulation, electricity produced per h = 22,419 kWh
therefore, the rate for purchase of electricity/kWh are

1) For electricity between 12,200 kWh and 14,000 kWh = 88.3 cs
2) For electricity between 14,000 kWh and 22,419 kWh = 98.3 cs

therefore, excess income over datum = (14,000–12,200) × 88.3
+ (22,419–14,000) × 98.3
= Rs. 9,865.28

**Calculation of total income**

Condition: Fiber % cane = 18
Imbibition % fiber = 300
Loss in income due to pol loss in bagasse per h = Rs. 2,357.51 (App. II)
Excess income from electricity per h = Rs. 9,865.28
therefore, total income per h over datum = Rs. (9,865.28–2,357.51)
= Rs. 7,507.77

**RESUME**

Des simulations de balances thermiques ont été faites pour deux tonnages de canne (150 TCH et 275 TCH), pour différentes teneurs en fibre % canne dans la fourchette 11% à 18% et pour des imbibitions % fibre allant de 150% à 350%. Une régression a été établie entre le pol % bagasse et l'imbibition % fibre. Les revenus combinés provenant de la vente de l'excédent d'électricité et du sucre additionnel
extrait ont été calculés et exprimés graphiquement en fonction de la fibre % canne pour chaque taux d’imbibition et pour chaque tonnage. Cette simulation indique qu’il serait plus rentable de limiter l’imbibition lorsque la fibre est supérieure à 14 et de l’augmenter lorsqu’elle tombe au dessous de 14%. Ces conclusions d’appliquent seulement à l’efficience thermique qui a été assurée au départ.

OPTIMIZACION DE LOS BENEFICIOS DE LA VENTA DE ELECTRICIDAD POR LAS FABRICAS DE AZÚCAR

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RESUMEN
Se realizaron simulaciones de los balances de vapor para dos capacidades de molienda (150 TCH y 275 TCH), para varios valores de % de fibra en caña, en el rango de 11 a 18 y para varios valores de imbibición % en fibra (150 a 350) para determinar la cantidad de electricidad que puede ser exportada para cada escenario. Se estableció una ecuación regresional para relacionar el pol % en bagazo y la imbibición % en fibra. Se calcularon los ingresos combinados de la venta de electricidad sobrante y del azúcar adicional extraído y se plotearon contra la fibra % en caña para cada razón de imbibición y capacidad. La simulación indicó que para las condiciones de eficiencia térmica asumidas, existirá una ventaja financiera en operar la fábrica a razones más bajas de imbibición para valores de la fibra % en caña mayores de 14%. Sin embargo, a un valor dado de fibra % en caña menor de 14% será más ventajoso incrementar la imbibición.

Palabras claves: Co-generación, balance de vapor, simulación, parámetros de proceso, eficiencia, beneficios, rentabilidad.