PROCESS ENERGY EFFICIENCY AND COGENERATION IN CANE SUGAR FACTORIES

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ABSTRACT

In a cane sugar factory with a cogeneration system, saving steam in the factory can increase the electricity production. With steam-conserving factory designs, we estimate that it would be possible to reduce the process steam demand in a raw cane sugar factory from about 400 to 250 kilograms per ton cane. If a high pressure condensing-extraction steam turbine cogeneration system were installed, steam economy retrofits could boost export electricity production by as much as 15%. This level of steam economy would also make highly efficient gasifier/steam-injected gas turbine cogeneration systems a future option. This technology could potentially produce about twice as much export electricity as high pressure steam turbine systems and could be commercialized within the next few years.

INTRODUCTION

With the recent trend towards diversification in the cane sugar industry, a growing number of factories are manufacturing one or more by-products (such as cogenerated electricity for export to the utility grid or alcohol) in addition to sugar and molasses. In a factory with several products, each of which requires a certain amount of energy (or bagasse) to manufacture, energy efficiency (both in the conversion of bagasse to useful energy and in the utilization of energy within the factory) can become more important. Some implications of energy efficiency improvements for a raw cane sugar factory with a cogeneration system are discussed here. Two types of bagasse fired cogeneration systems are considered. They potentially offer much higher electricity production than that found in most sugar factories today. They are: 1) high pressure condensing-extraction steam turbine systems and 2) steam injected gas turbines run on gasified bagasse.

In this paper "high pressure" (4.0-8.0 MPa) refers to boiler pressures typical of condensing-extraction steam turbines. "Medium pressure" refers to steam used for cane mills, which equals the boiler pressure in most sugar factories today (1.5-2.0 MPa). "Low pressure" refers to mill and turbo-alternator exhaust steam used in the process (0.2-0.3 MPa).

High pressure condensing-extraction steam turbine (CEST) cogeneration systems are now used in a few cane sugar factories (Anon[2], Kinoshita[10]) and are being considered for several others (Anon[3]). As has been demonstrated in Hawaii and Reunion, when small medium pressure (1.5-2.0 MPa) turbo-alternators, typical of those in most sugar factories (see Fig 1a), are replaced with a high pressure CEST sytem, the total electricity production can be increased from about 20 kilowatt-hours per ton of cane milled (kwh/tc), just enough to run the factory, to perhaps 70-120 kwh/tc. Thus, in addition to making sugar, about 50-100 kwh/tc becomes available for export to the utility grid (Fig lb). With

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a CEST cogeneration system, there would be an incentive to improve factory steam economy: any fuel (or steam) saved in the sugar process would become available for generating additional export electricity (Anon[2]).

In a gasifier/steam injected gas turbine (GSTIG) system, bagasse would be gasified to form a low BTU gas to fuel a gas turbine (Larson *et al*[12], Larson *et al*[13]). Steam would be raised for the mills and the manufacturing process in a heat recovery steam gererator (HRSG), using the hot exhaust gases from the turbine (Fig. 1c). Any steam not needed for the factory could be injected into the combustor to boost the electrical output of the system. While GSTIG systems are not commercially available at present, they could be developed within the next several years. Similar systems are being developed for use with coal in the US (Corman[7]). Piggy-backed onto this development, biomass-fired systems could become commercially available in the near term (Corman[8], Larson[11]).

GSTIG systems are of interest because they could potentially produce over 200 hwh/tc of export electricity, about twice as much as high pressure steam turbine systems (Larson *et al*[12], Larson *et al*[13]). However, GSTIG systems could not provide quite enough process steam to supply the average cane sugar factory. Thus, some factory steam economy measures would be required when using these systems.

The reasons for studying factory steam economy in raw cane sugar factories with cogeneration were: 1) to boost the production of export electricity from a particular type of cogeneration system, and 2) to widen future cogeneration options for the cane sugar industry to include the more efficient GSTIG systems. With these goals in mind, several steam-conserving retrofits, incorporating commercially available process equipment, have been assessed: heat exchangers which use hot condensate for juice heating, falling film evaporators, and continuous vacuum pans. In the 1970's, these technologies were widely adopted in oil-dependent process industries, with large evaporation energy requirements (such as the beet sugar, pulp and paper, and dairy industries) to reduce fuel costs (Rosenblad[15]). With the emphasis on by-products and process steam economy, they are beginning to appear in the cane sugar industry as well (Bourzutschky[6], Tobe[17]).

Although the focus has been on congeneration, energy efficiency improvements may also be of interest to factories with other by-products requiring energy (or bagasse) for their manufacture.

INCREASED COGENERATION OUTPUT THROUGH IMPROVED FACTORY STEAM ECONOMY

The electricity (in kwh/tc) and steam production (in kg of medium pressure steam produced per ton of cane or kg/tc) are shown in Fig. 2a for a high pressure condensing-extraction steam turbine (CEST) cogeneration system and for a gasifier/steam injected gas turbine (GSTIG) system based on the General Electric LM-5000 gas turbine (Larson *et al*[12], Larson *et al*[13]). Steam and electricity demands characteristic of most raw cane sugar factories today (Hugot[9]) are shown as ranges of values along the x and y axes of the graph. The steam and electricity production in a typical medium pressure steam driven turbo-alternator (T/A) sugar factory cogeneration system have also been plotted.

For both CEST and GSTIG cogeneration systems, the steam and electricity production can be varied over a range of operating conditions, so that more electricity can be produced when the steam demand is reduced. The right endpoint of each range indicates the maximum amount of process steam that could be produced with the particular cogeneration system; the left endpoint represents the maximum electricity production, which would occur when the process steam production is zero. Fig. 2 shows the calculated steam and electricity production at each endpoint. It has been assumed that electricity production increases linearly with decreasing steam demand (Hugot[9]).

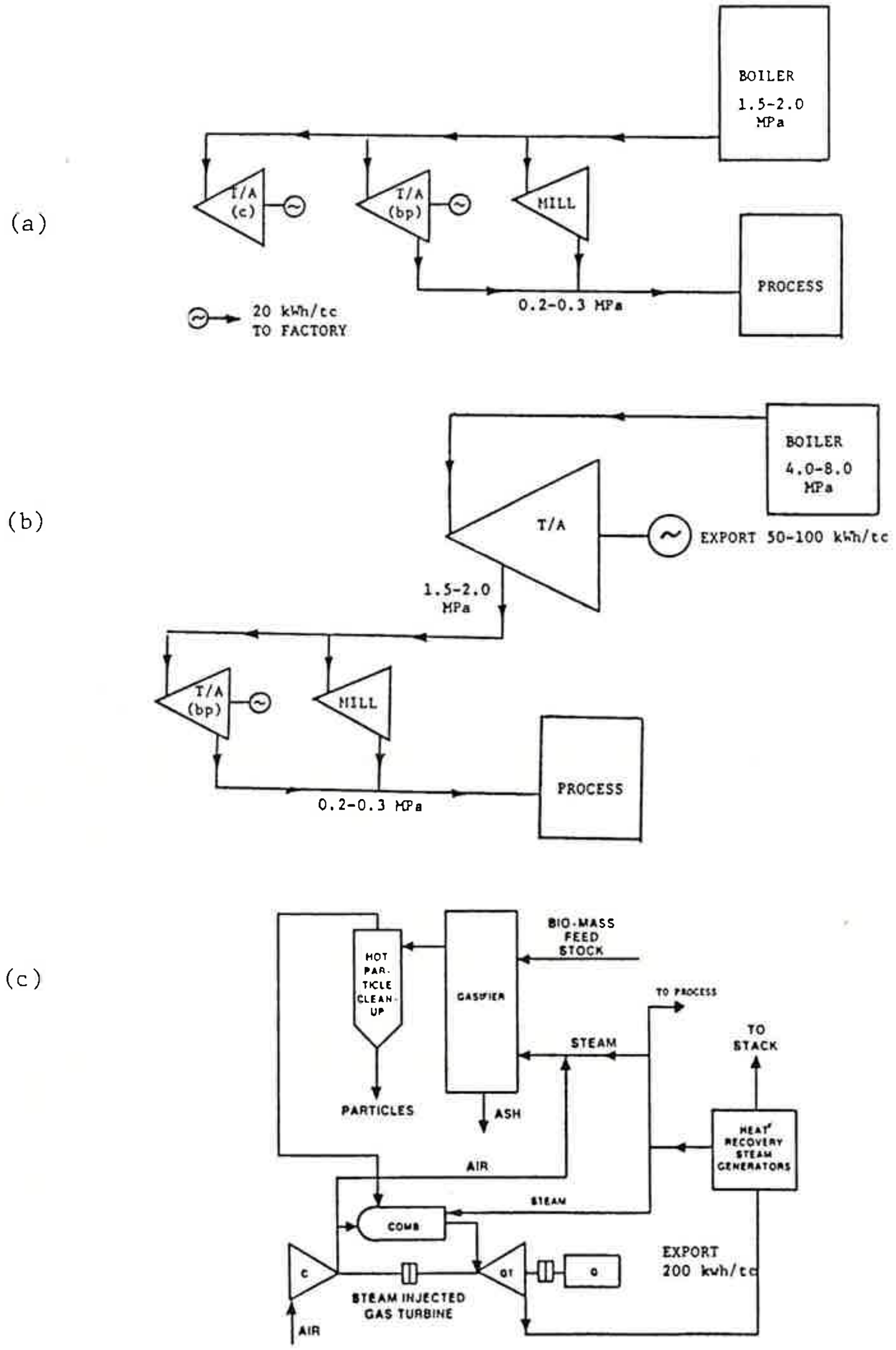

Figure 1 - A sugar factory with a cogeneration system: a) conventional steam turbine, b) high pressure condensing-extraction steam turbine - one extraction, c) gasifier/steam injected gas turbine system.

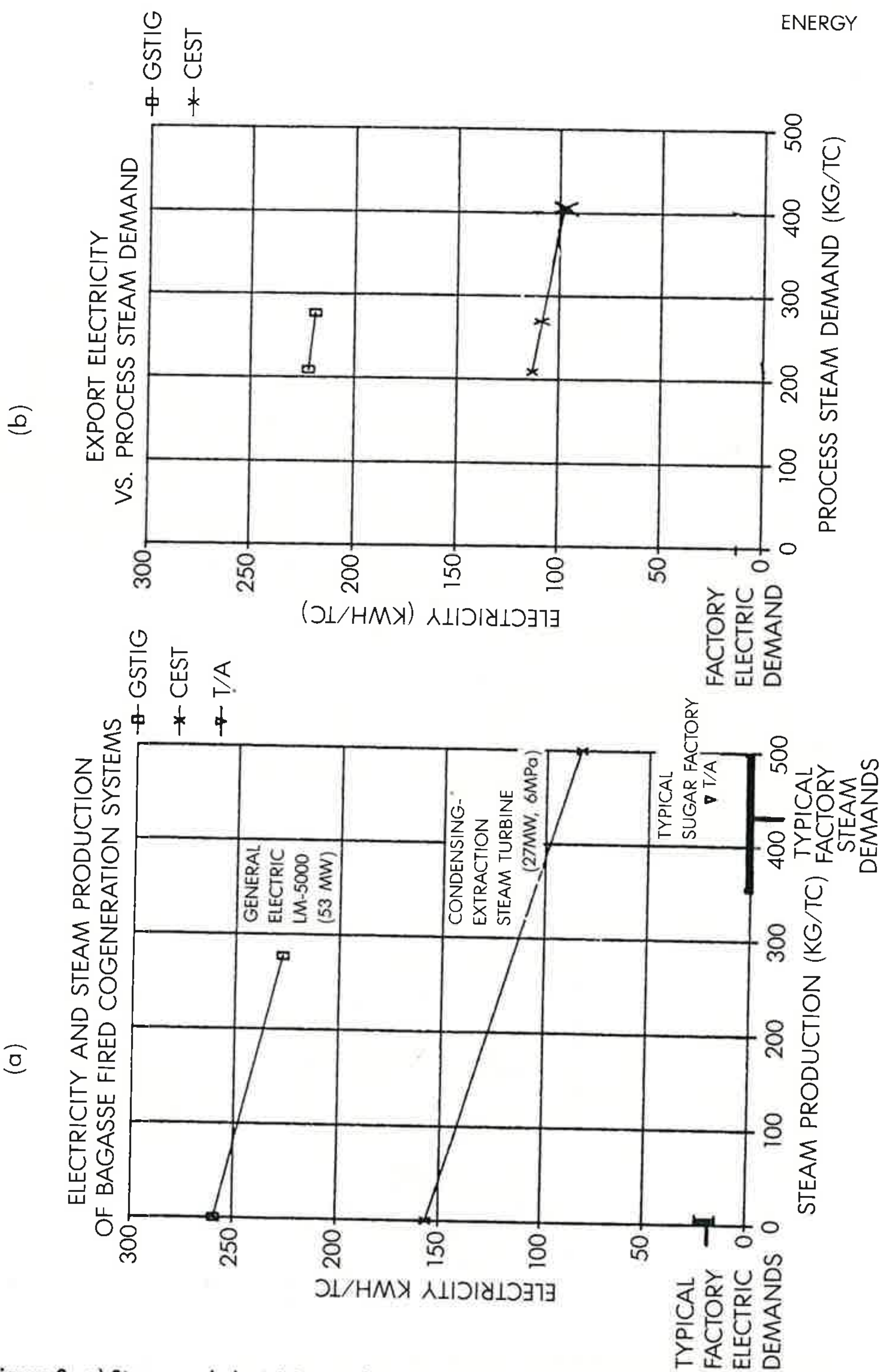

Figure 2 - a) Steam and electricity production estimates for cogeneration systems operating at cane sugar factories during the milling season with bagasse as fuel, b) export electricity production versus process steam demand.

Comparing typical factory demands to the output of the cogeneration systems, it can be seen that the CEST can easily meet the steam demands of the average raw sugar factory (350-500 kg/tc), while producing about 100 kwh/tc, roughly five times as much electricity as a small turbo-alternator system in a typical factory. While the GSTIG produces about 220-250 kwh/tc, or about twice as much electricity as the CEST system, the maximum steam production possible with the GSTIG system is only about 280 kg/tc. The GSTIG system would not be able to supply all the factory steam needs without some factory steam economy measures.

It is assumed that total electricity production includes the CEST or GSTIG cogeneration system output plus any electricity generated by small turbo-alternators in the factory (see Fig. 1). In this study, for each kilogram of process steam saved, it is assumed further that about 0.076 kwh of extra export electricity is produced by the CEST system (Ogden *et al*[14]). Then by subtracting the factory electricity demand from the total electricity production, the electricity available for export to the grid can be calculated as a function of process steam demand, for the CEST and GSTIG configurations in Fig. 1. The export electricity is shown for the CEST and GSTIG systems in Fig. 2b.

From Fig. 2b it can be seen that the potencial exists to boost significantly in-season export electricity production via factory steam economy. For example, for the CEST system, if the process steam demand were reduced from 400 kg/tc to 250 kg/tc, an extra 11 kwh/tc of electricity could be exported to the utility grid. For a factory grinding 175 tons of cane per hour, this would mean an extra 1.9 MW of exportable electric power in season. If the season were 210 days long, and the factory ran 23 hours per day, the added revenue over one season would be more than US $ 0.5 million, assuming that the electricity is worth US $ 0.06/kwh. Moreover, decreasing the factory low pressure process steam demand below 280 kg/tc would mean that the more electrically efficient GSTIG cogeneration systems could be used, still meeting factory process steam demands, and approximately doubling the electrical output when compared with a CEST system.

OPPORTUNITIES FOR CONSERVING FACTORY STEAM

The evaporators, juice heaters and vacuum pans are the largest users of low pressure process steam. Commercially available process equipment which could save energy at each of these steps should be considered.

Juice Heaters

In most factories, raw juice is heated in several stages with vapour bled from the evaporators (or sometimes with low pressure exhaust steam). Clear juice heaters typically use also vapour bled from the evaporator.

By using the plentiful hot condensate from the evaporator and vacuum pans (which has an average temperature around 100° C) a large part of the juice heating could be done and some steam could be saved. In many cane sugar factories, the pure portion of the condensate is returned to the boiler as feedwater. (Pure condensates are defined here as those derived directly from condensed exhaust steam, eg the steam condensed in the first effect of the evaporator and in the vacuum pans. Impure condensates are those derived from condensed juice vapours, eg condensates from the second and later effects of the evaporator or from steam bled to the vacuum pans or juice heaters).

In these factories, it may or may not be more efficient to send the pure condensates directly to the bolier, rather than using them first to heat juice. This tradeoff involves a number of factors, which depend on the factory design. For example, consider two options 1) pure condensate sent directly to the boiler at 90° C, 2) pure condensate used first for juice heating and then sent to the boiler at 40°C. If the boiler produces steam at 6.0 MPa, 480°C, the total enthalpy change is 3206 kJ/kg for 40°C feedwater, and 2996 kJ/Kg for 90° C feedwater. The energy required to make steam is about 7% higher with 40°C feedwater than with 90°C feedwater. The more energy efficient of the two options would depend on how much of the 7% energy difference must be provided by burning extra bagasse, and how much process steam would be saved, using the pure condensates for juice heating enroute to the boiler.

The heat contained in the impure condensates, however, is generally not recovered in sugar factories today. Depending on the evaporator and vacuum pan operating temperatures, the impure condensates could contain as much or more heat than pure condensates, and could accomplish at least some and possibly all of the juice heating. (In a falling film evaporator, the exhaust steam consumption, and therefore the pure condensate production, would be lower than in a Robert evaporator. The impure condensates would be hotter and more plentiful and more energy would be available from impure condensates for juice heating).

Either plate-and-gasket or shell-and-tube type heat exchangers could be used for juice heating with hot condensate. Plate-and-gasket heat exchangers have higher heat transfer coefficients than shell-and-tube heat exchangers. As the required heat exchanger surface areas would be reduced, they would be likely to be more compact and less expensive. The pressure drop would be similar to that of the shell-and-tube type heat exchangers (Anon[1]).

In a plate-and-gasket heat exchanger, it would be important to remove any large particles from the juice which could clog the narrow space between the plates. Experience in the beet sugar industry indicates that it is possible to screen potentially troublesome coarse particles (Bourzutschky[6]). Another possible application for plate-and-gasket heat exchangers is for heating clear juice.

Evaporators

In most cane sugar factories, forward feed, multiple effect, short tube rising film (or Robert) evaporators are used. Vapour is bled from the first two effects for juice heaters and vacuum pans. The first one or two effects run at slightly above atmospheric pressure, with the later stages running at a slight vacuum. Vapour from the final stage of the evaporator is fed into a barometric condenser to maintain a pressure gradient throughout the system.

Falling film evaporators are often used as energy savers in the beet sugar, pulp and paper and dairy industries, and are being studied for use in the cane sugar industry (Bourzutschky[6], Tobe[17]). They have the advantage of higher juice flow velocity and higher heat transfer coefficients and can, therefore, run at a smaller temperature difference between effects.

With an input steam temperature of 135°C, it is possible to run the entire evaporator at pressures above atmospheric and to use the vapour from the later effects for juice heating and vacuum pans. Because the juice travels through a falling film evaporator three to four times more quickly than in a Robert type, it is likely that higher input steam temperatures (up to 130-135°C) could be tolerated without damage to the juice due to inversion of sugars and colour formation. The issue of colour formation during evaporation is still a topic of research (Sangster[16]). However, results from the falling film evaporator operated by GTZ/SIRI in Jamaica indicate no problems with colour formation at these temperatures.

Vapour bleeding from later effects rather than from the first effect makes better use of the multi-effect configuration and reduces the overall steam consumption of the evaporator. Moreover, the condensate from the effects is at 100-125°C and in many cases could do all the juice heating. In existing factories with steam driven mills, the mill exhaust back pressure is already set and it may not be possible to produce exhaust steam at 135ºC. However, even with exhaust steam at 120ºC, it should be possible to run three or even four effects of a falling film evaporator under pressure.

Vacuum pans

In batch type or discontinuous pans, the thick syrup or massecuite is boiled down one batch at a time, in several stages or strikes. Because of the water added in washing, molasses dilution and agitation, it takes about 1.2-1.7 kg of steam to evaporate 1 kg of vapour from the massecuite in each pan. Steam consumption values reported in the literature range from 120-170 kg/tc (Hugot[9]), depending on the design of the vacuum pan.

The steam load varies greatly in individual discontinuous pans. When the syrup is introduced into the pan, evaporation proceeds very quickly and the steam demand is high. Then the steam demand of the pans drops due to the increased density of the massecuite. This variation is a disadvantage with cogeneration where constant steam loads are desirable.

Continuous vacuum pans have the advantage of lower steam consumption and constant steam loads, and are coming into increasing use (Hugot[9]). It is estimated that the steam consumption for a continuous pan should be about 25% less than for a discontinuous pan (Hugot[9]).

RESULTS OF STEAM ECONOMY CASE STUDIES

Four case studies of steam economy retrofits of a raw sugar factory (modelled on the Monymusk factory in Jamaica) with a CEST cogeneration system are presented here. In each case, the factory steam and material flows, and the heating surface areas of retrofit equipment (condensate juice heaters, falling film evaporators and continuous vacuum pans have been calculated). Using the capital costs for process equipment given at the bottom of Table 1, the total cost of each retrofit has been estimated.

Once the factory steam demand is known, the export electricity production can be determined from Fig 1. The extra export electricity with the retrofit is then calculated relative to the base case. Assuming an average grinding rate of 175 tons of cane per hour, a 210 day, 23 hour/day season, and an electricity price of US $ 0.06/kwh, the extra electricity revenue (due to decreased process steam demand) and the simple payback time for each retrofit have been computed. The results are summarised below and in Table 1 and Figs 3a-d.

Case 1: Base case conventional raw sugar factory (Fig 3a)

The base case is a conventional raw sugar factory modelled on the Monymusk factory in Jamaica. A description of the existing factory equipment and operating conditions (Blanchard[5]) was used as input to the sugar factory model, and the mass and heat flows were calculated, as shown in Fig 3a. The process low pressure steam demand was computed to be 381 kg/tc. The overall medium pressure steam demand including turbine losses is 405 kg/tc, (Table 1, Case 1).

Case 2: Condensate heat recovery for juice heating (Fig 3b)

In this case, the process steam demand, assuming heat recovery from the condensate for juice heating, was estimated. If all the condensate were used for heating, the overall steam demand would be reduced from 405 kg/tc to 358 kg/tc.

If a plate-and-gasket heat exchanger were used, the heating surface area required would

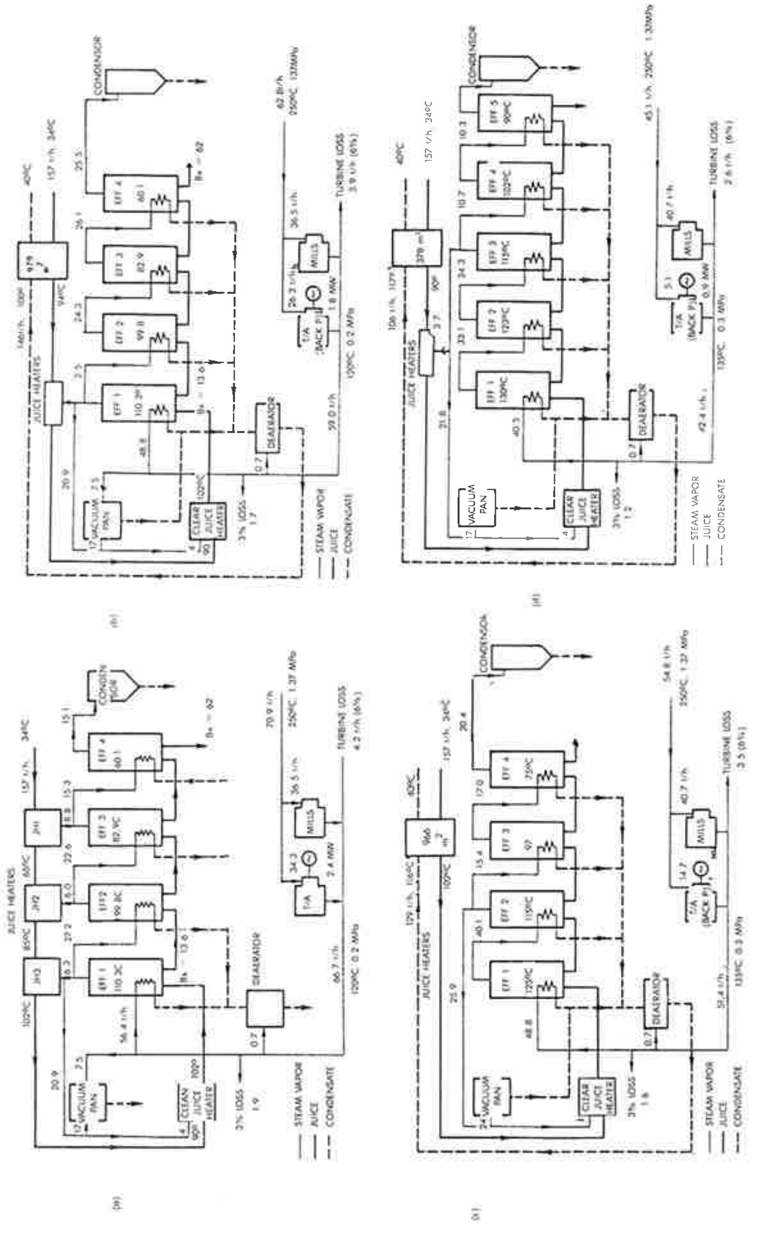

Figure 3 - Factory flows for steam economy case studies in Table 1: a) conventional factory based on the Monymusk factory in Jamaica (Case 1), b) conventional factory with condensate heat recovery for juice heating (Case 2), c) quadruple effect falling film evaporator with condensate juice heating (Case 3), d) quintuple effect falling film evaporator with condensate juice heating and continuous vacuum pans (Case 4).

Table 1 - Comparison of steam economy retrofits for a raw sugar factory
Grinding rate: 175 TCH, season - 210 days, 23 hours/day

Case	1 Present Monymusk W/CEST	2 W/Condensate Juice heater	3 Quad Fall. film Evaps	4 Quint Fall. film Evaps
Factory demands (a)				
Steam (kg/tc):				
Med pressure:	405	359	313	258
mills	209	209	229	229
turbo-alternators	196	150	84	29
6% loss	−24	−22	−19	−15
Low pressure:	381	337	294	242
evaporator	322	308	279	231
direct to vac pans	43	43	43	0
3% loss	11	10	9	7
Electricity (kwh/tc) (b)	12.8	12.8	12.8	12.8
Retrofit cost (US$) (c)				
Juice heater	-	147 000	144 800	56 700
Falling film Evap	-	-	2 400 000	2 400 000
Cont. Vacuum pans	-	-	-	622 000
TOTAL	-	147 000	2 544 800	3 078 700
Total electricity for export with CEST (kwh/tc)	94	97.5	101.0	105.2
Extra electricity for export (kwh/tc) (d) (Relative to Case 1)	0	3.5	7.0	11.2
Extra electricity revenue (1000 US$/season) (Relative to Case 1)	0	177	354	568
Simple payback time for retrofit (seasons)	-	0.8	7.1	5.4

(a) Factory balances are based on the sugar factory model described in Ogden *et al*[14]

(b) See Baldwin and Finlay[4].

(c) Assumed installed costs for shell and tube heat exchangers are $100/m^2, plate and gasket heat exchangers $150/m^2, evaporators and vacuum pans $500/m^2 (Anon[1], Rosenblad[15]).

(d) Assumed that a CEST cogeneration system is used, that an extra 0.076 kwh of export electricity is generated for each kg of medium pressure steam saved and that electricity is worth US $ 0.06/kwh.

be 979 m^2 and the cost would be US $ 147 000; for a shell-and-tube type the area would be 1957 m^2, and the cost US $ 196 000. The extra electricity production would be 600 kw, the revenue per season about US $ 177 000, and the payback time about one season (Table 1, Case 2). If only the impure condensate were used for heating, the medium pressure steam demand would be reduced to 389 kg/tc. The heating surface area of a plate-and-gasket juice heater would be 238 m^2, the cost US $ 37 500, the extra electricity production 213 kw, the extra revenue per season US $ 62 000 and the payback time less than one season.

Case 3: Quadruple effect falling film evaporator with condensate juice heating (Fig 3c)

In this case, it has been assumed that a quadruple effect falling film evaporator has been installed, and condensate used for juice heating. The overall medium pressure steam consumption would be reduced to 313 kg/tc, a saving of about 23%. The saving occurs largely because the first two effects run under pressure, so that vapour bleeding for the vacuum pans can be done from the second effect, rather than using first effect vapour or exhaust steam. In addition, no vapour bleeding for juice heating would be required. The area of the evaporator would be 4800 m^2, the juice heater would be 970 m^2. The total cost would be about US $ 2.5 million. The extra export electricity production with a CEST system would be 1225 kW (an increase of about 10%), the extra revenue US $ 355 000 per season, and simple payback time 7.2 seasons (Table 1, Case 3).

Case 4: Quintuple effect falling film evaporator with condensate juice heating and continuous vacuum pans (Fig 3d)

For higher steam economy, a quintuple effect falling film evaporator with condensate juice heaters and continuous vacuum pans could be installed. The total area of the evaporator would be 4800 m^2. The steam required would be reduced to 258 kg/tc with this design, a saving of 36%. The total retrofit cost would be about US $ 3.1 million. The extra export electricity would be 1960 kw (an increase of 12% when compared with case 1), the extra revenue would be US $ 574 000 per season, and the simple payback time would be 5.4 seasons.

The factory steam demand would be low enough with this design, that the GSTIG cogeneration system could be used, approximately doubling the export electricity production. Moreover, by making the relatively inexpensive factory steam economy investments necessary for the GSTIG, the overall economics of cogeneration could be significantly improved when compared with the CEST (Larson *et al*[12], Larson *et al*[13]).

While the simple payback period for Case 4 steam conserving retrofits with the CEST system would be rather long, the cost of steam economy investments would be quite modest compared to the total cogeneration investment, ie less than 10% of the cost of a new CEST or GSTIG cogeneration system (Larson *et al* [13]).

CONCLUSIONS

Using commercially available process equipment it appears to be possible to reduce the overall steam use in a raw cane sugar factory to about 250 kg/tc. If a high pressure condensing-extraction steam turbine cogeneration system were present, the export electricity production could be boosted by as much as 15% through steam economy. Steam conserving designs also make bagasse gasifier/gas turbine cogeneration systems a future possibility for use in the cane sugar industry. The export electricity from these systems could be about 220 kwh/tc or twice the amount possible with CEST systems today.

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