Biomass-fired steam-injected gas-turbine cogeneration for the cane sugar industry†

By Eric D. Larson*, Joan M. Ogden*, Robert H. Williams* and Michael G. Hylton**

Introduction

The study reported here was undertaken to assess the prospects for increasing the production of exportable electricity from sugar factories by the use of gas-turbine cogeneration systems, with residues from the cane as the primary fuel[1]. Gas turbines at sugar factories would represent a fundamental technological change, involving some risks, so their expected technical and economic performance must be far better than that of the commercially-established steam turbine before they could be considered for the sugar industry. To compare advanced gas-turbine and modern steam turbine cogeneration, a case study based on the Jamaican Monymusk factory was undertaken, with data drawn in large part from a study exploring the feasibility of installing a large condensing-extraction steam turbine cogeneration system at Monymusk[2].

Exporting electricity from sugar factories

Bagasse-fired cogeneration is familiar to the world's sugar industry, but few sugar factories generate excess electricity for export to national utility grids. A typical factory cogeneration system produces some 20 kWh of electricity per tonne of cane crushed (kWh/tc) – just enough to meet on-site demand. Such a system also leaves no excess bagasse, thereby avoiding disposal costs. A modern, large condensing-extraction steam turbine (CEST) cogeneration system, similar to that being considered for Monymusk and to those already installed at a few factories, e.g. in Hawaii[3] and Réunion[4], could export in excess of 100 kWh/tc, while meeting on-site energy demands. If steam-conserving process technologies widely used in oil-dependent industries like beet sugar and dairy products manufacture (e.g. condensate juice heaters, falling film evaporators, and continuous vacuum pans) were adopted at cane sugar factories, still more electricity (perhaps 25% more) could be exported to the grid. Furthermore, if an auxiliary fuel were used for power production in the off-season, the total electricity generation would be still higher – some 240 kWh/tc (Figure 1).

The biomass-gasifier steam-injected gas turbine (biomass-GSTIG) cogeneration system considered in the present study, if operated year-round at a "steam-conserving" factory would produce about 460 kWh/tc, or about double that for a CEST and 23 times as much as that produced at a typical sugar factory today (Figure 1).

GSTIG technology

The biomass-GSTIG system (Figure 2) would operate by converting the biomass feedstock into a combustible gas in a pressurized gasifier, which would be coupled to an aircraft-derivative steam-injected gas turbine. Some of the air from the gas turbine compressor would be used in the gasifier, and the combustible gas would be cleaned of particulates before burning it in a combustor with the balance of the compressor air. The hot turbine exhaust gases would raise steam in a heat recovery steam generator (HRSG); some of this steam would be required to operate the gasifier, and the rest could be used for process needs or for injection into the combustor. The injection of steam into the combustor leads to an increase in both power output and electrical efficiency. With steam injection,

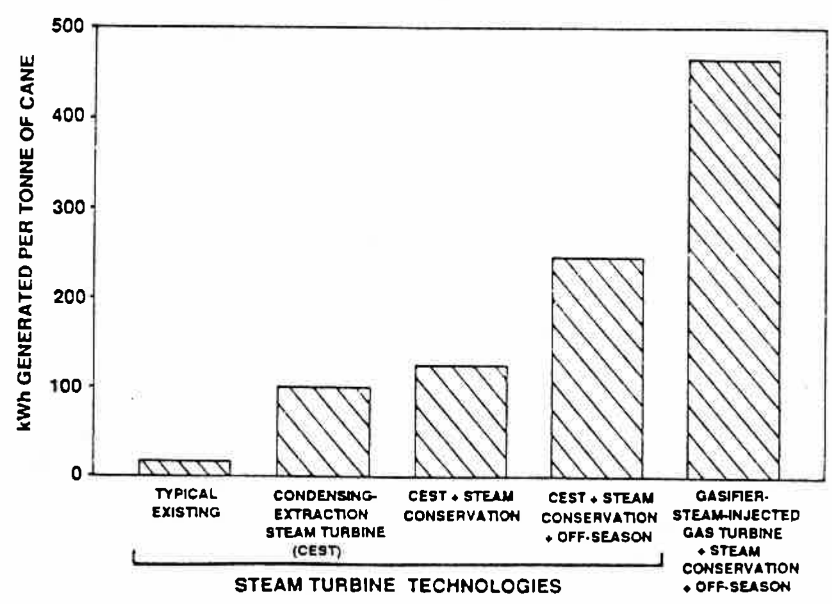

Fig. 1. Electricity generating potential of cane residue-fired condensing extraction steam turbine and gasifier steam-injected gas turbine cogeneration systems: The two right-most bars include the effects of reduced process steam demand and off-season operation with an auxiliary fuel[1]. Note that in all cases shown here the electricity production is referenced to the tonnage of cane processed during the milling season

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1 Larson *et al.*: "Steam-injected gas-turbine cogeneration for the cane sugar industry; optimization through improvements in sugar processing efficiencies". *PU/CEES Report 217* (Centre for Energy and Environmental Studies, Princeton University, Princeton, NJ), 1987.

2 Ronco Consulting Corporation and Bechtel National Inc.: Jamaica cane/energy project feasibility study, funded by the US Agency for International Development and the Trade and Development Program, Washington, DC, 1986.

3 Kinoshita: Unpublished data from Hawaiian Sugar Planter's Association, Aiea, Hawaii, 1986.

4 Directorate-General of Information and Market Innovation: "24.65 MW bagasse-fired steam power plant demonstration project". (EUR 10390 EN/FR, Commission of the European Communities, Brussels), 1986.

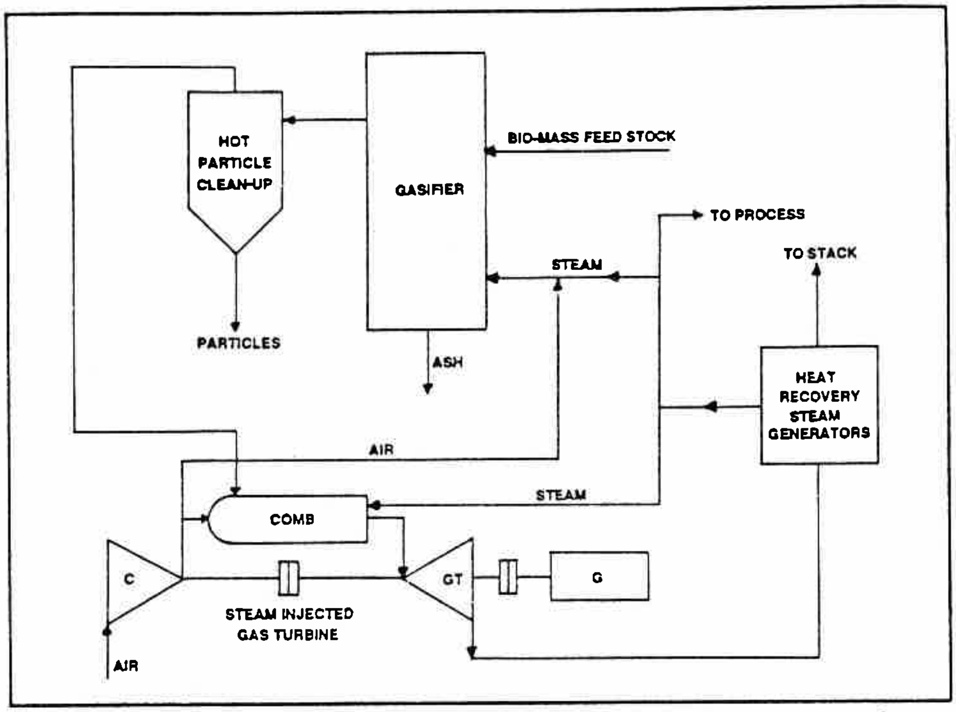

Fig. 2. Schematic representation of a biomass-gasifier steam-injected gas turbine (biomass-GSTIG) cogeneration cycle

the higher mass flow through the turbine expander increases power output. Higher efficiency is achieved largely because only a negligible amount of additional work input is required to pump the boiler feed-water to boiler pressure, avoiding the large amount of work required to compress a gaseous working fluid. Aircraft-derivative gas turbines are chosen for steam injection, because they are designed to accommodate turbine flows considerably in excess of their nominal ratings[5].

Steam-injected gas turbines fired with natural gas have been operating commercially in the United States for several years in cogeneration applications. This technology is attractive for cogeneration applications, because steam not needed for process can be injected to produce more power; under provisions of the Public Utilities Regulatory Policies Act (PURPA) in the US, the extra electricity can be sold to the utility at a reasonable price, thus extending the financial viability of gas turbine cogeneration to a wide range of variable steam-load applications[5]. (PURPA requires utilities to purchase cogenerated electricity at a price equal to the cost the utility could avoid by not having to supply that electricity otherwise.)

Steam-injected gas turbines fired with gasified coal (coal-GSTIG units) have been investigated by the General Electric Company (GE) in the US, with support from the Department of Energy (USDOE)[6], following the successful commercial demonstration of a gas-turbine steam-turbine combined cycle operating on gas derived from sulphur-bearing coal at the 100 MW Cool Water central station power plant in California[7]. [In a gas turbine/steam turbine combined cycle, the hot exhaust from a simple-cycle gas turbine is used to raise steam in a HRSG, which in turn is used to drive a condensing steam turbine, which augments the power production of the gas turbine. Industrial (not aircraft-derivative) gas turbines are most often used in combined cycles.]

Coal-GSTIG technology is largely transferable to systems based on biomass. In fact, the higher reactivity of biomass makes it inherently easier to gasify than coal[8]. Furthermore, most biomass contains no sulphur, obviating the need for, and additional cost of, the sulphur removal equipment. Thus, no new technology must be proven to use biomass in GSTIG systems[9]. In fact, by linking with the ongoing work on coal-GSTIGs, the commercialization of the biomass-GSTIG technology could be accomplished in about three years[9].

Performance/cost estimates of biomass-cogeneration technologies

Performance: Fuelled by bagasse during the milling season, both CEST and GSTIG cogeneration systems could produce variable amounts of electricity and process steam, as the simplified representation in Figure 3 indicates. To increase electricity production in a CEST, a greater fraction of the steam would be condensed rather than extracted; in a GSTIG, a greater fraction of the steam produced in the HRSG would be injected into the combustor. At any level of process steam production, a GSTIG unit would produce roughly twice as much electricity per tonne of cane as a CEST (Figure 3). However, the maximum level of process steam production for the GSTIG systems considered here is about 300 kg/tc, while the CEST could produce in excess of 400 kg/tc.

The total steam produced in the HRSG of a GSTIG would be in excess of 300 kg/tc. It is estimated, however, that the Lurgi-type gasifier considered here would require (primarily for cooling the bed) about 20% of the total steam production, which is based on the steam requirements when gasifying coal in this type of gasifier[6]. The gasification steam required with biomass may actually be lower, although sufficient testing with biomass feedstocks has not been carried out to determine this. An

5 Larson & Williams: *ASME J. Eng. for Gas Turbines and Power*, 1987, **109**, (1), 55 - 63.
6 Corman: "System analysis of simplified IGCC plants" (General Electric Company, Schenectady, NY, USA for the US Dept. of Energy), 1986.
7 Electric Power Research Institute: "Cool Water coal gasification program: fourth annual progress report AP-4832" (EPRI, Palo Alto, CA, USA), 1986.
8 Larson *et al.*: "Biomass gasification for gas turbine power generation", in "Electricity", Eds. Johansson *et al.* (Lund University Press, Lund, Sweden), 1989, pp 697 - 739.
9 Corman: "Integrated gasification-steam injected gas turbine (IG-STIG)" presented at Workshop on Biomass-Gasifier Steam-Injected Gas Turbines for the Cane Sugar Industry, (Washington, DC), 1987.

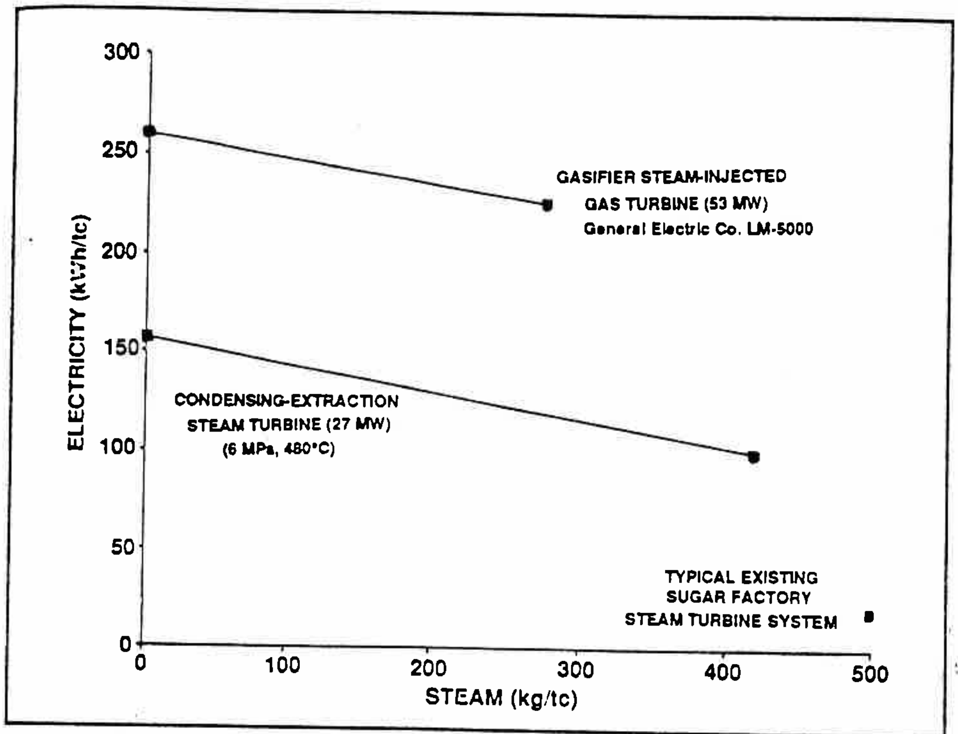

Fig. 3. Steam and electricity production estimates for CEST and GSTIG cogeneration systems operating at sugar factories during the milling season with bagasse as fuel[1]. The steam and electricity demands for typical existing factories are shown for comparison

alternative gasifier, e.g. a pressurized fluidized-bed unit such as the Rheinbraun High-Temperature Winkler unit, may require virtually no steam, since its normal operating temperature without steam would be relatively low[8,10].

Matching the process steam available from the cogeneration system with the steam demands at a sugar factory is discussed below.

Capital costs: Installed unit capital costs have been estimated for several sizes of CEST and GSTIG systems (Figure 4)[1]. (The United States GNP deflator has been used to express all costs in this paper in constant 1985 US dollars.) Unit costs are higher for CEST systems, and they have stronger associated scale economies. Unit costs for the GSTIG would be lower because of their substantially higher energy efficiency and reduced materials requirements (e.g. no condenser or cooling tower). In addition, scale economies would be weaker than for the CEST systems, since even in the larger sizes it is expected that shop fabrication, rather than field assembly, could be used extensively.

Also shown for comparison in Figure 4 is a cost estimate for a new 61 MW coal-fired central station power plant, which is discussed below. This was previously identified in a report for the Jamaica Public Service Company (JPS) as the least costly electricity supply expansion option for Jamaica[11].

Maintenance: Maintenance costs are a key consideration for gas turbines. They are widely believed to be relatively high, based primarily on the electric utility experience with peaking gas turbines. Indeed, with low capacity factors and repeated starts and stops, such units often have high per-kWh maintenance costs[12]. However, with the proper maintenance programs that accompany most gas turbines operating in baseload applications, the costs can be quite modest. For example, the Dow Chemical Company has operated several natural-gas-fired Pratt and Whitney FT-4 aircraft-derivative gas turbines (15 - 20 MW each) in cogeneration plants in the San Francisco area for some twenty years, with total maintenance costs averaging 0.2 - 0.3¢/kWh[12].

Minor maintenance of aircraft-

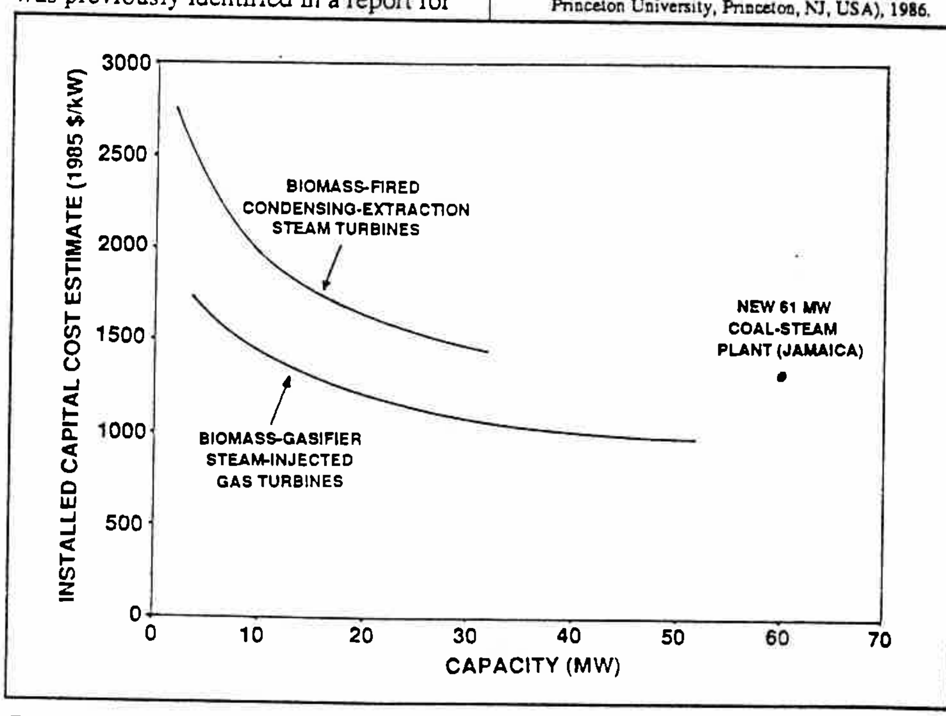

Fig. 4. Estimated unit capital costs for biomass-fired CEST and GSTIG cogeneration systems[1] for a new 61 MW central station coal/steam plant in Jamaica[11]

10 Bellin *et al.*: *Bioenergy 84*, 1985, 3, 65 - 72.

11 Montreal Engineering Company: "Least-cost expansion study" *Rpt. prepared for the Jamaica Public Service Co. Ltd.*, 1985.

12 "Workshop on steam-injected gas turbines for central station power generation" Eds. Larson & Williams (New Jersey Energy Conservation Laboratory, Center for Energy and Environmental Studies, Princeton University, Princeton, NJ, USA), 1986.

derivative gas turbines, upon which GSTIG systems would be based, is facilitated by the modular design of these engines originally developed to minimize down-time for aircraft. Major maintenance is typically done off-site, while a replacement engine continues to produce power. The replacement engines are often leased or purchased from manufacturers as part of a service agreement. In other cases, manufacturers provide innovative service contracts which guarantee delivery and installation of a replacement engine within a specified period of a major engine failure (e.g. 48 hours), which is made possible by the very compact nature of aircraft-derivative machines. Stationary gas turbines, including many aircraft-derivative units, are operating in industrial applications worldwide[1] with relatively low maintenance costs.

Table I provides a summary of the cost assumptions used in the financial analysis discussed in the next section. Maintenance cost estimates were based on previous studies and discussions with industry experts[1]. The operating labour estimates are based on employment data for power plants operated by JPS[11].

Table I. Cogeneration costs assumed in the financial analysis[1]

Cogeneration system	CEST	GSTIG
Capacity, MW	27	53
Unit cost \$/kW	1560	990
Total installed cost, 10^6\$*	42	53
Fixed maintenance, 10^3\$/year	660	1300
Variable maintenance, \$/kWh	0.003	0.001
Number of operating employees	24	55
Labour cost, 10^3\$/year	130	300

* If steam conservation retrofits are made at the factory, this cost would increase by \$3.1 million (Table II)

Table II. Summary of factory end-use scenario[1,14]

Equipment/Retrofits	Cost, 1985 US\$	Factory energy use: Steam, kg/tc *,** (Live)	Steam, kg/tc *,** (Exhaust)	Electricity† (kWh/tc)
Conventional factory:				
No retrofits	0	209	374	13.0
Steam-conserving factory:		209	209	13.0
Plate/gasket juice heater	100,000			
5-Effect falling film evaporator	2,400,000			
Continuous vacuum pan	600,000			
Total	3,100,000			

* Steam conditions are 1.4 MPa, 250°C for live steam and 120°C, saturated for exhaust steam

** For the conventional factory, it is assumed that the existing turbo-alternators are operated to produce all on-site electricity, in which case all of the cogenerated power would be exported, and all steam (374 kg/tc) would be supplied to the factory as live steam. For the steam-conserving factory, the turbo-alternators would be retired, and the cogeneration plant would supply on-site electricity needs

† With a new cogeneration system installed, the previously-existing boiler system (including fans, pumps, and other electrical ancilliaries), which accounts for approximately 1/3 of the electricity demand at a typical factory[15], would be shut down. The electricity demands shown here are with a new cogeneration system. Note that elsewhere in this paper, the electrical output of the CEST and GSTIG systems are specified as net of the cogeneration plant

Jamaican case study: A sugar producer's perspective

To explore the financial feasibility of exporting electricity, internal rates of return have been calculated for CEST and GSTIG cogeneration plants installed at hypothetical raw sugar factories.

Assumptions

Factory operation: The operation of the Monymusk factory, processing a nominal 175 tch during a 206-day season, was chosen as the basis for developing the hypothetical factory energy demands. Monymusk has operated for the last several years with an average cane throughput of 150 - 160 tch, which is below its rated capacity of over 200 tch, because of inadequate cane supplies and deteriorating factory equipment[13]. With World Bank supported rehabilitations to field irrigation systems as well as the processing plant, plans are to raise the throughput to 200 tch, or a total of over 755,000 tonnes per season, by 1990.

Two levels of sugar factory energy demands considered in this study are summarized in Table II and discussed in detail elsewhere[1,14]. The total steam requirement of 374 kg/tc for the "conventional" sugar factory is based on the performance of existing equipment at Monymusk. To utilize a GSTIG cogeneration system, which would produce a maximum of about 300 kg/tc of process steam (see Figure 3 and "Performance" above), equipment retrofits would be required at a typical factory to reduce steam demand. Decreasing steam demand would also permit a greater amount of electricity to be exported from the CEST. A "steam-conserving" factory considered here would utilize condensate juice heating, falling film evaporators, and continuous vacuum pans to reduce the steam demand to 209 kg/tc, or that available from the mill turbine exhaust (Table II).

Exported electricity price: In principle, the price a utility pays a cogenerator for electricity should reflect the cost the utility avoids by not having to supply that electricity itself, e.g. by building new capacity or operating existing plants. The lowest cost of alternative new central station electricity

13 "Jamaica Sugar Holdings, Ltd. corporate plan 1984 - 1989. (III) Monymusk factory and estate technical report." (Tate and Lyle Technical Services, Bromley, England), 1984.

14 Ogden *et al.*: *I.S.J.*, In press.

15 Baldwin & Finlay: *Proc. 1987 Meeting Jamaican Assoc. Sugar Tech.*, in press.

Table III. Levelized fuel prices assumed for the Jamaica case study

Fuel	Price (1985 US$/GJ)
Bagasse (from Eletrobras report[16])	
As delivered from mills, 50% moisture content	0.00
Dried to 25% moisture	0.58
Baled, dried to 25% moisture and stored	0.78
Briquetted (12% moisture)	1.16
Pelletized (15% moisture)	2.02
Barbojo	
Baled, dried to 25% moisture, transported and stored*	0.97
Briquetted, transported and stored (12% moisture)**	1.35
Pelletized, transported, and stored (15% moisture)**	2.21
Residual fuel oil	
Low[17]	2.90
High	4.00
Distillate fuel oil	
Low[17]	5.40
High	7.50
Imported coal	
Low[17]	1.43
High[11]	2.08

* Estimated in the Ronco and Bechtel study[2]; the barbojo would dry in the field to roughly 35% moisture, after which it would be baled. It is estimated that it would have a moisture content of about 25% by the time it is used at the cogeneration plant

** Calculated as the cost of baled barbojo ($0.97/GJ, which includes transport and storage costs) plus the difference in cost between baling and either briquetting or pelletizing bagasse

supplies (including capital, fuel, and O&M charges) in Jamaica is estimated to be 5.0 - 5.8¢/kWh for a new 61 MW coal/steam plant. This assumes an installed cost of $1316/kW (which includes a portion of the costs of building a national coal-handling system), a heat rate of 12,030 kJ/kWh, a 66% annual capacity factor, an annual labour cost of $358,000, maintenance costs of 0.3¢/kWh, a discount rate of 12%, and a 30-year economic life[11]. Assumed coal costs are given in Table III.

Another set of cost estimates[2] for Jamaica are: 8.3¢/kWh for a new coal-fired steam-electric plant, 6.6¢/kWh for a new oil-fired steam-electric plant, and 8.7¢/kWh for a new oil-fired gas turbine plant. The cost of operating existing oil-fired plants (O&M and fuel only) in Jamaica is estimated to be 4.5 - 6.1¢/kWh, assuming a heat rate of 14,500 kJ/kWh and an O&M cost of 0.3¢/kWh[11]. The assumed costs of residual fuel oil are given in Table III.

Bagasse costs: During the milling season, a CEST unit would burn unprocessed (50% moisture content) bagasse, for which no cost is charged. For the GSTIG systems it is currently unknown what level of processing of the bagasse will be required for gasification. Five levels that are considered here, and their associated costs, are shown in Table III.

Costs of off-season fuel: Since a cogenerator would often need to operate year-round to earn an avoided cost that includes a capacity credit, several off-season scenarios are considered here.

The tops and leaves of the cane, "barbojo" in Jamaica, is assumed to be the off-season fuel for the base case, cost estimates for which are given in Table III. The harvesting and storage of barbojo for energy has not been done on a large commercial scale. However, field trials or small-scale operations have been conducted in Puerto Rico[18], the Dominican Republic[19], the Philippines[20], Mauritius[21], Thailand[22] and Florida[23], and tests are underway in Jamaica. In Puerto Rico, where extensive field trials with three varieties of cane have been carried out, an average of 660 kg of 50% moisture content barbojo were produced with each tonne of cane. (Left on the field after cutting, the barbojo dried from about 50% to 35% moisture within 6 days.) One approach being pursued in Jamaica[24] has been to focus on developing cane varieties that will retain most of their leaves through harvesting, with the

16 Eletrobras: "Aproveitamento energético dos resíduos da agroindustria da cana- de-açúcar," (Ministry of Industry and Commerce, Brasilia, Brazil), 1986.
17 JPS projections to the year 2000, quoted by Ashby (Centre for Special Studies, PCJ Engineering, Kingston, Jamaica): *Personal communication*, 1987.
18 Phillips: "Cane crop residue for biomass fuel." (Agricultural Engineering Department, University of Puerto Rico, Mayaguez), 1986.
19 Vinas: *Paper presented at the Second Pacific Basin Biofuels Workshop*, Hawaii, 1987.
20 Varua: *ibid.*.
21 Deepchand: *I.S.J.*, 1986, **88**, 210 - 216.
22 Coovattanachai: *Personal communication*, 1987.
23 Eiland & Clayton: *Paper presented at the Amer. Soc. Agric. Engineers Winter Meeting*, Chicago, 1982.
24 Shaw: *Personal communication*, 1987.

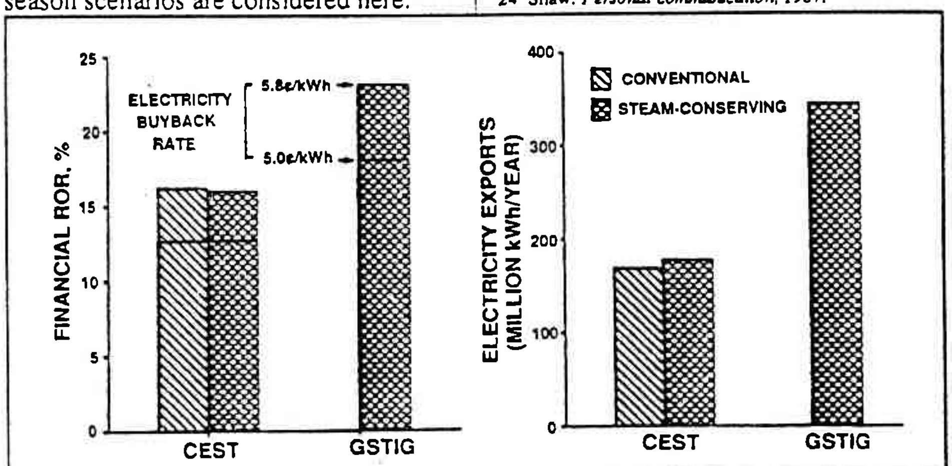

Fig. 5. Financial rates of return and annual electricity exports for cogeneration and process-equipment investments at "conventional" and "steam-conserving" factories described in Table II. Table I gives cost assumptions for the cogeneration facilities. A thirty-year economic life is assumed in all calculations

whole cane being transported to a central location where the barbojo and millable cane would be separated.

Initial trials in some cane growing regions indicate that increased weed growth and decreased soil moisture retention associated with barbojo removal are not serious problems there. Of greater concern appears to be potential damage to an emerging crop and soil compaction (particularly of clay soils, as in Jamaica) on ratooned fields during mechanical collection of barbojo. In any case, while some level of barbojo recovery appears feasible, longer-term studies are required to fully assess the agronomic effects.

Since barbojo recovery is unproven, a second off-season scenario is considered in which oil is burned during the off-season for the first five years of operation, followed by a switch to barbojo. The CEST systems would burn residual fuel oil, and the GSTIG would burn distillate fuel oil. The lower oil prices shown in Table III are assumed for operation during this five-year period, since these are the prices currently used[17] in JPS projections to the year 2000.

Results

Base-case: The annual exports of electricity and the estimated financial rate of return (ROR) for alternative cogeneration investments at factories with two levels of process energy demands are shown in Figure 5. The cogeneration systems considered here are sized for fuelling with the bagasse available from the processing of 175 tch: a 27 MW CEST or a 53 MW GSTIG. An investment in the CEST plant at a "conventional" factory is estimated to provide a ROR of 13 - 16%, if barbojo were the off-season fuel. With additional investments in process equipment required for a "steam-conserving" factory, slightly more electricity could be exported, but the ROR would be virtually unchanged (Figure 5), since the extra investment costs (Table II) would offset the extra electricity revenues. Investing in the GSTIG system (fuelled by briquetted bagasse and barbojo) and "steam-conserving" retrofits would provide an estimated ROR of 18 - 23%, and exports of electricity would be about double that for the CEST (Figure 5). (The Lurgi dry-ash gasifier, which is considered for the GSTIG systems analysed here, was originally designed to gasify chunks of coal. The biomass fuel, therefore, may need to be in a form similar to coal chunks. If an alternative gasifier were considered, e.g. a Rheinbraun High-Temperature Winkler fluidized-bed unit[10], less processing of the bagasse might be required, with dramatic impacts on cost.) The total tonnage of barbojo required for the off-season with the CEST would be about three-quarters of the total bagasse tonnage consumed during the milling season. For the GSTIG, bagasse and barbojo consumption would be comparable.

At the "steam-conserving" factory up to $23 of electricity revenue would be generated per tonne of cane crushed, if GSTIG cogeneration were used and if the electricity buyback rate were 5.0¢/kWh. Sugar revenues would equal electricity revenues for a sugar price of about 23¢/kg. For comparison, electricity revenues with the CEST would equal sugar revenues for a sugar price of about 11¢/kg.

Impact of alternative fuels: The "steam-conserving" case is chosen here to illustrate the impact of using alternative fuels. If less extensive processing than briquetting of bagasse and barbojo were required for the GSTIG, the ROR would increase from a range of 18 - 23% up to a range of 24 - 29% while, if pelletizing were required, it would fall to 11 - 16%.

For the scenarios in which oil is burned during the first five off-seasons, the ROR for the GSTIG would be 11 - 13%, while that for the CEST would be 10 - 12%. The ROR for the GSTIG falls relatively further from that for the base case since the GSTIG would burn distillate fuel oil, while the CEST would burn less costly residual fuel oil.

In a third scenario, the cogeneration system could be undersized relative to the in-season fuel supply, and exce bagasse stored for use during the off-season (after processing to permit lon term storage). In this scenario, about ! as much electricity would be produce annually, and the ROR would be 14 - 18% for the GSTIG (using briquetted bagasse year-round) and 10 - 13% for the CEST (using baled, dried bagasse during the off-season[1]).

Results for smaller installations

The average cane processing capacity of sugar factories in Jamaica and many other countries is lower tha 175 tch. Since there are scale econom associated with both the CEST and GSTIG technologies (see Figure 4), th ROR would decrease in both cases fo cogeneration investments at smaller factories. However, because of its weaker scale economies, the financial advantage of the GSTIG relative to th CEST would increase with decreasing size. For a "steam-conserving" factor processing about 20 tch, the ROR wo be 9 - 13% for a 5 MW GSTIG unit (fuelled by briquetted cane residues) a 3 - 5% for a 3 MW CEST (using less-processed cane residues)[1].

(to be continu

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International seminar on sugar and cane derivatives[1]

The Cuban Institute for Research on Sugar Cane Derivatives (ICIDCA), in conjunction with the Cuban Institute f Sugar Research (ICINAZ) and Tecnoazúcar, will hold a second Internationa Seminar on Sugar and Cane Derivative during April 10 - 13, 1990. Topics wil include sugar technology, biotechnology, food and animal feed, treatment a use of wastes, development of bagasse agglomerates, and pulp and paper technology. The deadline for submittin papers has passed but further information may be obtained from the organiz ing committee at Via Blanca 804, Carretera Central, Havana, Cuba (Tele: 511667, 511022).

1 *GEPLACEA Bull.*, 1989, 6, (11), Sugar Inf.-1.

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Case study: Utility perspectives

Jamaican context

While the GSTIG would provide much more attractive rates of return to a sugar producer than would a CEST plant, the capital involved (Table I) would be far in excess of investments to which sugar producers are accustomed. By contrast, the investments in a GSTIG unit would typically be less than what an electric utility might invest in building a comparable amount of new central station capacity (Figure 4). In addition, the capacity increment of a single GSTIG would be smaller than a typical new central station power plant, allowing a utility to better match the evolution of electricity supply and demand.

For a utility, cogenerated electricity would be of interest if it cost less than other utility sources. Fuelled by briquetted cane residues at a "steam-conserving" factory, the GSTIG would produce exportable electricity for about 4.1¢/kWh, and the CEST would produce about half as much electricity for about 4.8¢/kWh. In the scenarios involving oil as the off-season fuel the costs would be about 5.2¢/kWh for the GSTIG and 5.4¢/kWh for the CEST. These cogeneration costs are compared in Figure 6 with the cost of power from a new 61 MW coal-fired power plant, which is being considered by JPS as a least-cost expansion option. It would produce electricity for an estimated total cost of 5.0 - 5.8¢/kWh (see the section "Exported electricity price" above). In all cases shown in Figure 6, the GSTIG plant would provide comparable- or lower-cost electricity than the new coal-fired option, even with a low price for coal.

The cost of cogenerated electricity is also compared in Figure 6 with the *operating* cost of existing oil-fired power plants, which would range from 4.5 to 6.1¢/kWh (see the section "Exported electricity price" above). For all cases where biomass is the sole fuel, the GSTIG facility would produce electricity at a lower cost, even with oil at $2.9/GJ ($19/bbl). Under these conditions, it would be economically worthwhile to scrap existing oil-fired plants and replace them with new GSTIG facilities.

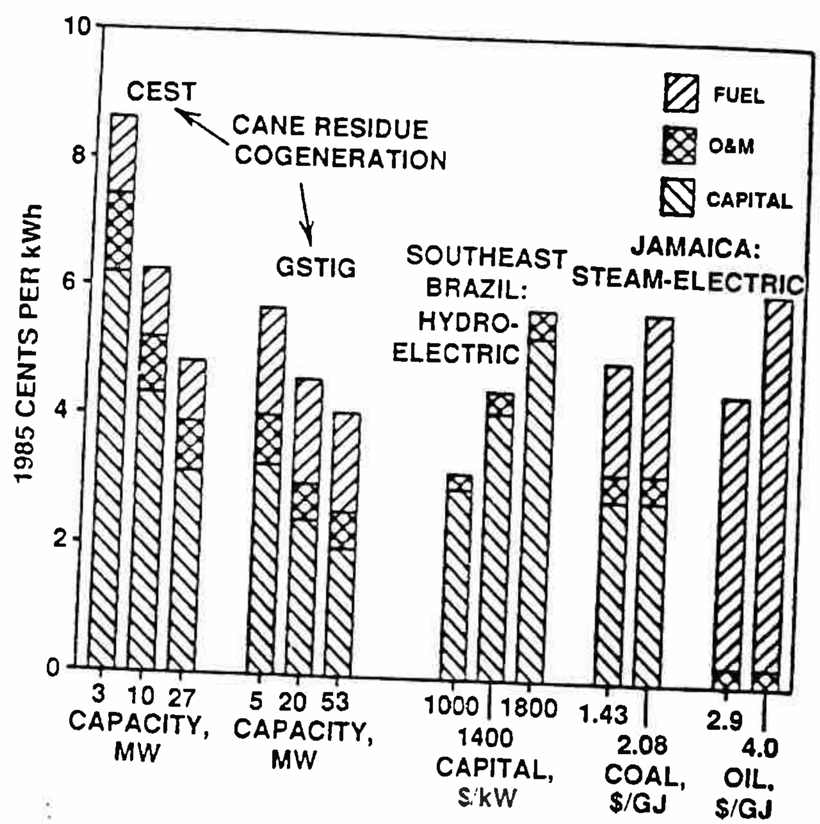

Fig. 6. Estimated levelized cost of generating exportable electricity with CEST and GSTIG cogeneration systems at a "steam-conserving" sugar factory and for three central-station alternatives[1]. Total costs are shown for a new 61 MW coal-steam plant in Jamaica and new hydro-electricity plants supplying power to Southeast Brazil. Also shown is the cost of operating existing oil-steam plants in Jamaica. Table I gives cost assumptions for the largest CEST and GSTIG plants. Assumptions for the smaller plants are in the Larson *et al.* report[1]

If Jamaica's total resources of cane residues were to be exploited for power, some existing oil-fired generating capacity could be retired, new central-station power plant construction could be deferred for many years or perhaps decades, and substantial foreign exchange would be saved. A typical 1980's cane harvest (2.2 million tonnes) would support nearly 80 MW of CEST units that could export about 500 million kWh of electricity annually, or over 150 MW of GSTIG units that could export about 1000 million kWh per year. For comparison, JPS generated 1437 million [illegible] power were to displace new coal-fired capacity, up to $270 million dollars of foreign earnings might be saved over the 30-year life of the plants (Table IV). If cogenerated power displaced electricity from existing oil-fired units, up to $300 million might be saved (Table IV). Per kWh cogenerated, the savings with GSTIG would be 50 - 90% greater than with CEST.

Southeast Brazilian context

Southeast Brazil, where much of Brazil's sugar cane grows and which includes the heavily industrialized state of São Paulo, provides an interesting contrast to Jamaica, because it is a cane-producing region which relies heavily on hydro-electric power, which is a much less costly electricity ...

Table IV. Potential foreign exchange savings to Jamaica with alternative cogeneration systems (at the 1985 level of cane production) by avoiding construction of new utility central station coal-fired capacity or by displacing existing oil-fired capacity*. For this analysis, all capital is assumed to be foreign exchange

Generating technology	Potential new capacity, MW	Required capital investment, $10^6$$	Life cycle foreign exchange requirements for fuel, $10^6$$**	Life cycle foreign exchange savings with cogeneration *vs.* coal or oil-fired central station $10^6$$**	$/MWh
CEST cogeneration†	79	132	0		
vs. New coal-steam†† with coal at:					
$1.43/GJ	88	116	70	54	3.54
$2.08/GJ	88	116	102	86	5.64
vs. Existing oil-steam†† with oil at:					
$2.9/GJ	0	0	172	does not apply‡	
$3.2/GJ	0	0	190	58	3.81
$4.0/GJ	0	0	237	92	6.89
GSTIG cogeneration†	153	160	0		
vs. new coal-steam†† with coal at:					
$1.43/GJ	172	226	138	204	6.84
$2.08/GJ	172	226	200	266	8.92
vs. Existing oil-steam†† with oil at:					
$2.9GJ	0	0	337	177	5.94
$3.2/GJ	0	0	372	212	7.11
$4.0/GJ	0	0	464	304	10.2

* For a cane production of 2.2 million tonnes per year, and CEST and GSTIG export electricity production of 231 and 452 kWh/tc, respectively. Thus, the CEST and GSTIG systems would produce 500 and 1000 GWh/year, respectively

** For a 12% discount rate and a 30-year life cycle

† Assuming all of the capacity is installed at a cost of $1671/kW for CEST and $1048/kW for GSTIG, which includes factory retrofits for a "steam-conserving" factory, and calculated capacity factors of 73% for CEST and 74% for GSTIG

†† Assumptions associated with the cost of electricity from the coal-steam plant and the oil-steam plant are given in the subsection entitled "Exported electricity price"

‡ CEST power would not displace oil-fired power unless the price of oil is at least $3.2/GJ, where the fuel plus operating cost for the oil-fired plants would equal the total generating cost for the CEST (4.9¢/kWh)

Table V. Estimated potential worldwide GSTIG generating capacity at sugar factories with the 1985 level of sugar cane production (assuming 10 tonnes cane per tonne of sugar[27])

Region	Potential electrical capacity, MW*
South America	17,800†
Asia	14,000
Central America	10,100
Africa	4,900
Oceania	2,700
United States	1,900
Europe	200
Total	51,600

* Assuming a 206 day season, 24 hour/day operation, 90% plant availability, and a GSTIG fuel requirement corresponding to 172 tonnes of cane per hour for a 53 MW unit

† Includes capacity that would be installed at alcohol production facilities in Brazil

demand in São Paulo growing at 8 - 10% per year[25], the installation of new hydro-electric capacity is under consideration. Since nearly all of the economical potential has already been exploited in the South, however, new hydro-electric plants would be built in the Amazon, with transmission lines connecting them to São Paulo[26]. Electricity from such facilities is estimated to cost from 3.2 to 5.8¢/kWh, depending primarily on the siting of the facility (Figure 6).

Based on the calculations for the Jamaican case study, large (53 MW) GSTIG cogeneration plants operating year-round on briquetted cane residues at sugar factories in São Paulo could supply electricity at a cost in the mid-range of those estimated for new hydro supplies, and small units would be competitive with the higher-cost hydro-electric plants. By contrast, only the larger CEST units would be competitive and then only with the higher-cost hydro-electric plants (Figure 6).

25 "Balanço energético do Estado de São Paulo 1984," (Conselho Estadual de Energia, São Paulo, Brazil), 1986.

26 Correa: *Personal communication*, 1987.

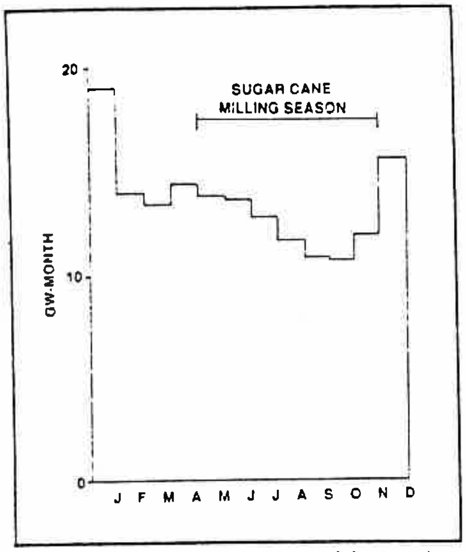

Fig. 7. The current hydro-electricity supply "trough" for a typical rain year, and the cane milling season in the state of São Paulo, Brazil[1]

Given the shortage of capital in Brazil (as in many other developing countries), the capital charges alone for electricity may be as important as the total cost of generation, in which case the GSTIGs would have a significant advantage at any scale. For example, the capital charges for GSTIG power would be 50 to 80% of those for hydro-electric capacity costing $1400/kW (Figure 6). For CEST, only a modest capital advantage would be gained, and only with larger units.

Even if GSTIG units were operated only during the milling season, the produced power may be attractive to the utilities if hydro-electric and GSTIG options were considered together. Since the cane milling season coincides with the dry season, cogeneration at sugar processing facilities could help fill the hydro-electric power "trough," (Fig. 7), thus making greater use of the installed hydro-electric capacity.

Implications

The introduction of GSTIG units world-wide could have a significant impact in over 70 countries that grow cane. The amount of cane residues produced globally in 1985 would support over 50.000 MW of GSTIG capacity, most of which would be in developing countries in Asia and Latin America (Table V). Based on an extrapolation of the results for Jamaica, some 300 × 10⁹ kWh of electricity could be produced at the 1985 level of cane production (Table VI). This is more than a quarter of the electricity generated by utilities in these countries in 1982, and is comparable to the level of electricity generated with oil.

A global transition to GSTIG cogeneration offers challenges for both the sugar and electric utility industries.

Table VI. GSTIG electricity generating potential in 10^9 kWh per year using the 1985 level of cane production (A) and the actual total electric utility generation in 1982 (B) in developing countries[1]

	A	B
Asia		
India	31.6	129.5
China	19.0	327.7
Thailand	10.8	16.2
Indonesia	7.6	11.9
Philippines	7.4	17.4
Pakistan	6.4	14.9
Taiwan	3.4	45.0
Iran	0.90	17.5
Vietnam	0.81	1.69
Burma	0.45	1.52
Bangladesh	0.42	2.98
Malaysia	0.32	11.1
Nepal	0.12	0.284
Sri Lanka	0.07	2.07
Sub-total	89	600
Central America		
Cuba	35.5	10.8
Mexico	15.7	73.2
Dominican Republic	4.2	2.38
Guatemala	2.3	1.42
El Salvador	1.2	1.45
Nicaragua	1.1	0.945
Honduras	1.0	1.04
Costa Rica	1.0	2.42
Jamaica	0.94	1.30
Panama	0.72	2.71
Belize	0.49	0.065
Barbados	0.45	0.339
Trinidad	0.36	2.30
Haiti	0.23	0.352
St. Kitts	0.12	not available
Sub-total	65	101
South America		
Brazil	95.0	143.6
Colombia	6.1	21.3
Argentina	5.5	36.2
Peru	3.3	7.25
Venezuela	2.1	39.0
Ecuador	1.3	3.09
Guyana	1.1	0.255
Bolivia	0.78	1.40
Paraguay	0.36	0.569
Uruguay	0.23	3.47
Surinam	0.05	0.17.
Sub-total	116	256
Africa		
South Africa	11.4	109.0
Egypt	3.7	17.2
Mauritius	3.1	0.320
Zimbabwe	2.1	4.16
Sudan	2.0	0.910
Swaziland	1.8	0.075
Kenya	1.6	1.73
Ethiopia	0.87	0.618
Malawi	0.69	0.410
Zambia	0.64	10.3
Ivory Coast	0.57	1.94
Tanzania	0.47	0.720
Madagascar	0.45	0.342
Cameroun	0.32	2.15
Zaire	0.30	1.48
Senegal	0.30	0.631
Mozambique	0.26	3.25
Somalia	0.24	0.075
Nigeria	0.23	7.45
Angola	0.23	1.46
Uganda	0.15	0.569
Congo	0.11	0.195
Mali	0.09	0.080
Gabon	0.05	0.530
Burkina Faso	0.05	0.123
Chad	0.04	0.065
Guinea	0.02	0.143
Sierra Leone	0.02	0.136
Benin	0.02	0.016
Liberia	0.01	0.389
Rwanda	0.01	0.066
Sub-total	32	166
Oceania		
Fiji	1.6	0.241
Papua New Guinea	0.13	0.441
Sub-total	2	1
All cane sugar-producing developing countries	304	1124

27 "Sugar Yearbook 1985", (International Sugar Organization, London), 1986.

In the sugar factories, the introduction of steam-conserving process technologies would probably be required, and year-round operation of the cogeneration plant would be beneficial. The development of barbojo recovery systems would be desirable to supply fuel for the off-season. Since investments in a cogeneration plant would typically be large by comparison with traditional investments in the sugar industry, creative financing and ownership arrangements may be desirable, e.g. utility and/or third-party participation.

For candidate GSTIG manufacturers, the potential markets appear large enough to justify the development effort that would be required to commercialize the technology, and the projected growth of the sugar industry worldwide – 1.5% per year through at least the mid-1990's[28] – would ensure secure markets in the future. The potential GSTIG market may be still larger if cane-based fuel alcohol comes into wide use. Preliminary calculations indicate that GSTIG cogeneration would be well-suited for the production of electricity at alcohol distilleries[1]. Although the fuel alcohol industry is developed on a large scale today only in Brazil, this situation may change if oil prices rise considerably in the next 10 - 15 years, as is expected. The US Department of Energy projects rising oil prices in a tightening world market, e.g. residual fuel oil for US utilities is projected to cost $4.3/GJ - $6.4/GJ in the year 2000 compared with $2.27/GJ in 1986[29].

Conclusions

Steam-injected gas-turbine cogeneration at sugar factories, using gasified cane residues as fuel, would be technically and economically attractive. The modern jet-engine-based technology, on which GSTIG cogeneration would be based, would be appropriate technology for firing with biomass in Jamaica and other countries for a number of reasons:

(i) The natural, economical scale of the technology is small (5 - 50 MW), which is well-suited for use with a diffuse energy resource like biomass.

(ii) For a utility, GSTIG capacity additions would typically be small in relation to the size of the utility grid in most developing countries, making it easier to keep evolving demand and supply in balance.

(iii) Widespread operation of GSTIG systems could lead to lower average electricity prices in many countries.

(iv) Because GSTIGs would be based on aircraft-derivative gas turbines, a sophisticated local maintenance capability is not required as a prerequisite for introducing the technology. Most major repairs would be done off-site, while replacement engines (flown or trucked in from centralized facilities) continue to produce power.

(v) Utilizing indigenous, renewable resources, GSTIG technology could reduce dependence on imported energy supplies, leading to savings in foreign exchange.

(vi) For GSTIG suppliers, potential markets exist which could justify the needed commercialization effort. The global market potential with existing levels of cane production is some 50,000 MW of capacity, and sugar demand is projected to grow 1.5% annually through the mid-1990's.

(vii) GSTIG units may also provide favourable economics at fuel alcohol distilleries, even with today's oil prices. The cane processing plant of the future may be one which produces electricity from a GSTIG as its primary product, with sugar and/or alcohol as co-products.

(viii) By producing power at competitive costs in rural areas GSTIG technology installed at sugar factories could help promote rural industrialization, thus providing rural employment and helping to curb urban migration.

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Summary

Considerable amounts of power could be produced at cane sugar factories for export to the utility grid (while meeting on-site energy needs) by adopting more energy-efficient cogeneration and sugar processing technologies. With off-season operation of the power plant using an auxiliary fuel (e.g. stored cane tops and leaves), still larger quantities of electricity could be exported. Modern condensing-extraction steam turbines have been installed in several factories world-wide. By comparison with these, steam-injected gas turbines fired with gasified biomass, which could become commercially available within a few years, offer higher thermodynamic efficiencies, lower unit capital costs, and weaker scale economies. A case study based on the Jamaican Monymusk factory indicates attractive rates of return on gas turbine investiments, compared with those for steam turbines. Gas turbines have the potential to provide some 1000 GWh per year of electricity using the cane residues presently produced in Jamaica. Globally, over 50,000 MW of gas turbine capacity could be supported with the 1985 level of cane residue production. The costs of producing this electricity is

28 Brown: "The international sugar industry: development and prospects." (Commodity Working Paper 18, World Bank), 1987.

29 "Annual Energy Outlook" (Energy Information Administration, US Department of Energy, Washington, DC), 1987.

estimated to be lower than the estimated costs for power from most central station alternatives, including hydro-electricity.

Co-generación de turbinas a gas inyectadas con vapor y alimentadas con biomasa para la industria del azúcar de caña

Cantidades considerables de energía podrían ser producidas en fábricas de azúcar de caña para exportar a la red de servicios (al mismo tiempo que proveer la energía necesaria en el sitio) adoptando la co-generación y tecnologías de procesamiento de azúcar con mayor eficiencia energética. Cuando la planta de poder opera fuera de temporada usando un combustible auxiliar (e.g. cogollos y hojas de la caña guardados), se pueden exportar cantidades aun mayores de electricidad. En muchas fábricas alrededor del mundo se han instalado turbinas a vapor modernas de extracción y condensación. Al ser comparadas con éstas, las turbinas de gas inyectadas con vapor y alimentadas con biomasa gasificada, que podrían estar disponibles comercialmente dentro de unos pocos años, ofrecen una eficiencia termodinámica mayor, costos de instalación unitarios más bajos y alzas más bajas. Un estudio de casos basado en la fábrica Monymusk en Jamaica indica tasas de retorno atractivas en las inversiones de turbinas a gas, comparadas con aquellas de turbinas a vapor. Las turbinas a gas pueden proveer potencialmente alrededor de 1000 GWh (giga-watt-horas) de electricidad por año usando los residuos de caña producidos en el presente en Jamaica. En forma global, más de 50,000 MW (megawatt) como capacidad de turbinas a gas podría ser logrado con el nivel de producción de residuos de caña de 1985. Los costos de producción de esta electricidad se estiman ser más bajos que los costos de energía estimados en la mayoría de las estaciones centrales alternativas, incluyendo la hidro-eléctrica.

Utilisation en industrie de canne d'une turbine à gaz avec injection de vapeur obtenue en brûlant de la biomasse

En améliorant l'efficience de l'utilisation de l'énergie, et des technologies de fabrication de sucre, on a pu produire des quantités considérables de courant pouvant être exporté vers les lignes utilitaires, et cela tout en répondant aux besoins propres en énergie. En mettant la station en route en dehors de la campagne (tout en utilisant une source énergétique auxiliare comme par ex. des feuilles et residus de canne), on a pu exporter encore davantage de courant électrique. Partout dans le monde on a installé dans plusieurs usines des turbines à vapeur modernes à condensation et soutirage. Lorsq'on les compare aux turbines à gaz à injection de vapeur brûlant de la biomasse gazéfiée (machines qui pourront être disponibles sur le marché dans quelques années), ces dernières offrent une meilleure efficience thermodynamique. Elles coûtent en outre moins cher et elles présentent moins d'économie suivant l'échelle. Une étude sur base de l'usine Monymusk en Jamaique indique des rendements financiers attractifs d'un investissement pour une turbine à gaz, comparée aux conditions pour une turbine á vapeur. Les turbines à gaz présentent un potentiel pour la production d/environ 1000 gWh par an d'èlectricité. Elles utiliseraient les résidus de la canne actuellement produite en Jamaique. De manière globale, les résidus de canne produites en 1985 permettraient une capacité des turbines á gaz équivalente á 50,000 MW. On estime que le coût pour produire ce courant électrique serait inférieur au coût correspondant au courant produit par la plupart d'autres stations alternatives, y compris l'électricité hydraulique.

Malawi experience in fuel ethanol production and utilization

continued from page 61

Summary

The history of the fuel ethanol industry in Malawi is discussed and the impact of the decisions made in the early 1980's on the industry today and its future are examined. The experience gained in the use of ethanol in a range of automotive applications is reviewed.

Experiencia Malawi en la producción y utilización del alcohol como combustible

Se discute la historia de la industria del combustible etanol y se examina el impacto de las decisiones tomadas a comienzos de los años 1980 sobre la industria de hoy y su futuro. Se revisa la experiencia ganada en el uso del etanol en un rango de aplicaciones automotrices.

L'expérience au Malawi dans la production et l'utilisation d'alcool-carburant

On discute de l'histoire de l'industrie de l'éthanol-carburant au Malawi et on examine quel en fut l'impact sur l'industrie d'aujourd'hui et quel sera l'avenir des décisions prises au début des années 80. On passe en revue l'expérience acquise dans l'usage de l'éthanol dans le domaine des moteurs pour voitures.

Erfahrung in Malawi mit Ethanolerzeugung- und -verwertung

Der Verfasser diskutiert die Brennstoffethanolindustrie in Malawi und betrachtet den Effekt von in den frühen 1980en gemachten Entscheidungen auf die heutige Industrie und ihre Zukunft. Gegeben wird eine Übersicht über die Erfahrung, die man mit dem Einsatz von Ethanol über eine ganze Reihe von Kfz-Anwendungen gemacht hat.