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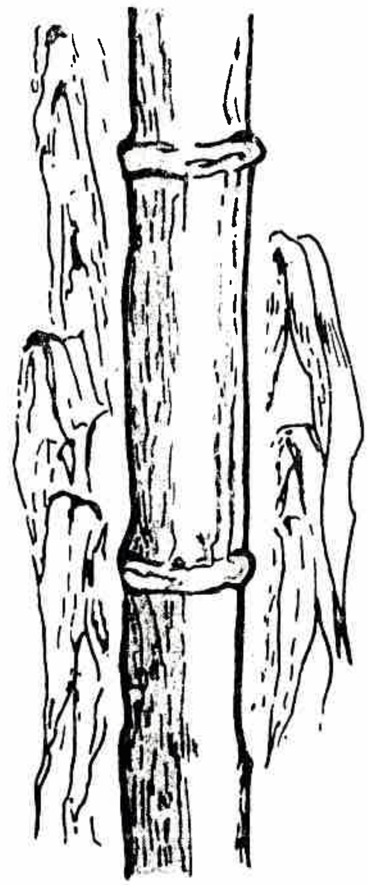

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PROCEEDINGS

BIOMASS-FIRED STEAM-INJECTED GAS-TURBINE COGENERATION FOR THE CANE SUGAR INDUSTRY

by

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ABSTRACT

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 worldwide. By comparison to 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 investments, compared to those for steam turbines. Gas turbines have the potential to provide some 1000 GWh per year of electricity using the presently produced cane residues 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 estimated to be lower than the estimated costs for power from most central station alternatives, including hydro.

INTRODUCTION

This study 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 (Larsen et al., 1987). 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 (CEST) cogeneration system at Monymusk (Ronco Inc., 1986).

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 would produce some 20 kWh of electricity per tonne of cane crushed (kWh/tc)--just enough to meet on-site demand. Such a system would also meet on-site steam demands and leave no excess bagasse. 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 (Kinoshita, 1986) and Reunion (Directorate, 1986), 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 (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 was used for power production in the off-season, the total electricity generation would be still higher--some 240 kWh/tc (Fig. 1)[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 (Fig. 1).

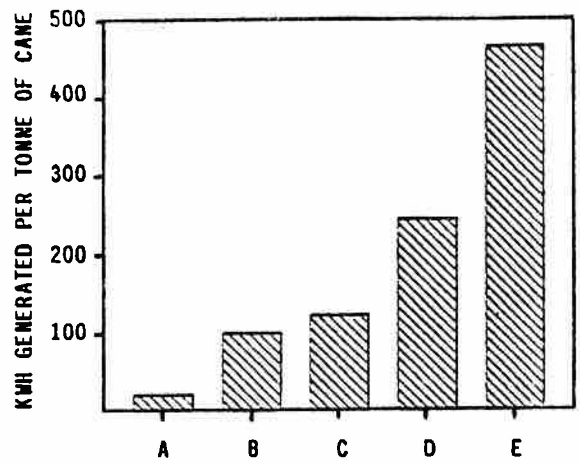

Fig.1. Electricity generating potential of cane-residue-fired condensing-extraction steam turbine and gasifier steam-injected gas turbine cogeneration systems. The two right-most bars include the effects of reduced process steam demand and off-season operation with an auxiliary fuel.[1]

GSTIG TECHNOLOGY

The biomass-GSTIG system (Fig. 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 which would be required to operate the gasifier and the rest of which 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.[2]

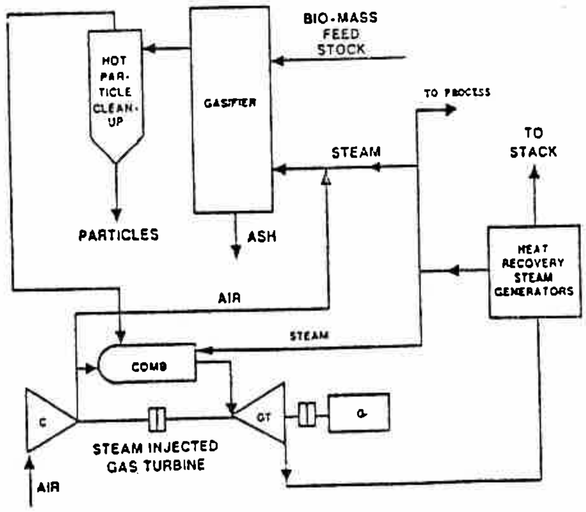

Fig. 2. Schematic representation of a biomass-gasifier steam-injected gas turbine (biomass GSTIG) cogeneration cycle).

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,[3] thus extending the financial viability of gas turbine cogeneration to a wide range of variable steam-load applications (Larson et al., 1987).

Steam-injected gas turbines fired with gasified coal has been under development by the General Electric Company (GE) in the US, with support from the Department of Energy (USDOE) (Corman, 1986), following the successful commercial demonstration of a gas turbine-steam turbine combined cycle[4] operating on gas derived from sulfur-bearing coal at the 100-MW Cool Water central station power plant in California (Electric, 1986). As of the time of this writing, however, an agreement between the USDOE and GE to continue this $156 million "clean coal" program had not been reached. A key goal of the coal-GSTIG program is the development of a system for removing sulfur from the hot combustible gas, which would considerably improve the system's efficiency compared to the cold-scrubbing system used at Cool Water. Should the clean coal program proceed, GE indicates that a commercial-scale demonstration of the hot-gas sulfur-removal technology would be undertaken within one year, followed within 3 years by the startup of a 5-MW coal-GSTIG pilot plant and within 6 years by the startup of a 50-MW commercial demonstration plant (Corman, 1987).

The 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 (Antal, 1978).

Furthermore, most biomass contains no sulfur, obviating the need for, and additional cost of, the sulfur removal equipment. Thus, no new technology must be proven to use biomass in GSTIG systems (Corman, 1987). In fact, by "piggy-backing" onto the ongoing work on coal-GSTIGs, the commercialization of the biomass-GSTIG technology could be accomplished in about 3 years (Corman, 1987).

PERFORMANCE AND 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 Fig. 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 (Fig. 3). However, the maximum level of process-steam production for the GSTIG systems considered here is about 300 kg/tc,[5] while the CEST could produce in excess of 400 kg/tc. Matching the available process steam with the steam demands at a sugar factory is discussed below.

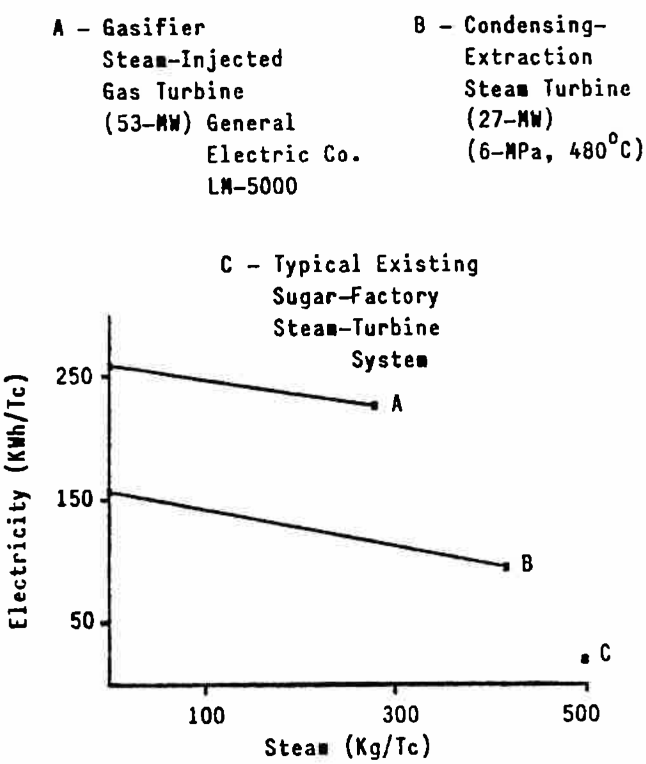

Fig. 3. Steam and Electricity production estimates for CEST and GSTIG cogeneration systems operating at sugar factories during the milling season with bagasse as fuel.[1]

Costs

Capital: Installed unit capital costs have been estimated for several sizes of CEST and GSTIG systems[6] (Fig. 4) (Larson et al., 1987). 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 material 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.

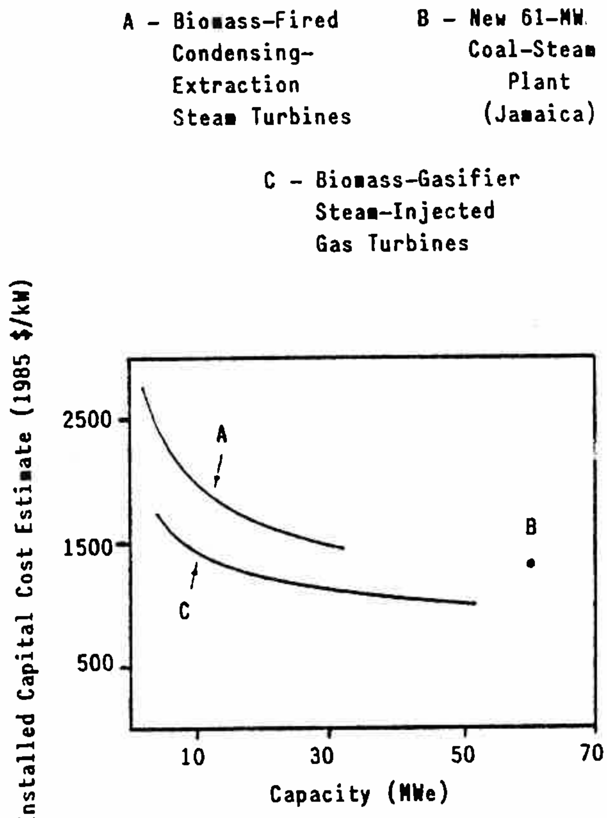

Fig. 4. Estimated unit capital costs for biomass-fired CEST and GSTIG cogeneration system,[1] and estimated capital cost for a new 61-MW central station coal-steam plant in Jamaica.[11]

Also shown for comparison in Fig. 4 is a cost estimate for a new 61-MW coal-fired central station powerplant, which is discussed below. This was previously identified in a report for the Jamaica Public Service Company (JPS) (Montreal, 1985) as a least-cost expansion option for Jamaica.

Maintenance: Maintenance costs are a key consideration for gas turbines. They are 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 (Larson and Williams, 1986). However, with the proper maintenance programs that accompany most gas turbines operating in baseload applications, the costs can be quite modest.[7]

Minor maintenance of aircraft-derivative gas turbines, upon which GSTIG systems would be based (see Note b), is facilitated by the modular design of the machines 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 (anywhere in the world) 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 aero-derivative machines.

With relatively low maintenance costs, stationery gas turbines, including many aircraft-derivative units, are operating in industrial applications worldwide (e.g., see Fig. 5)

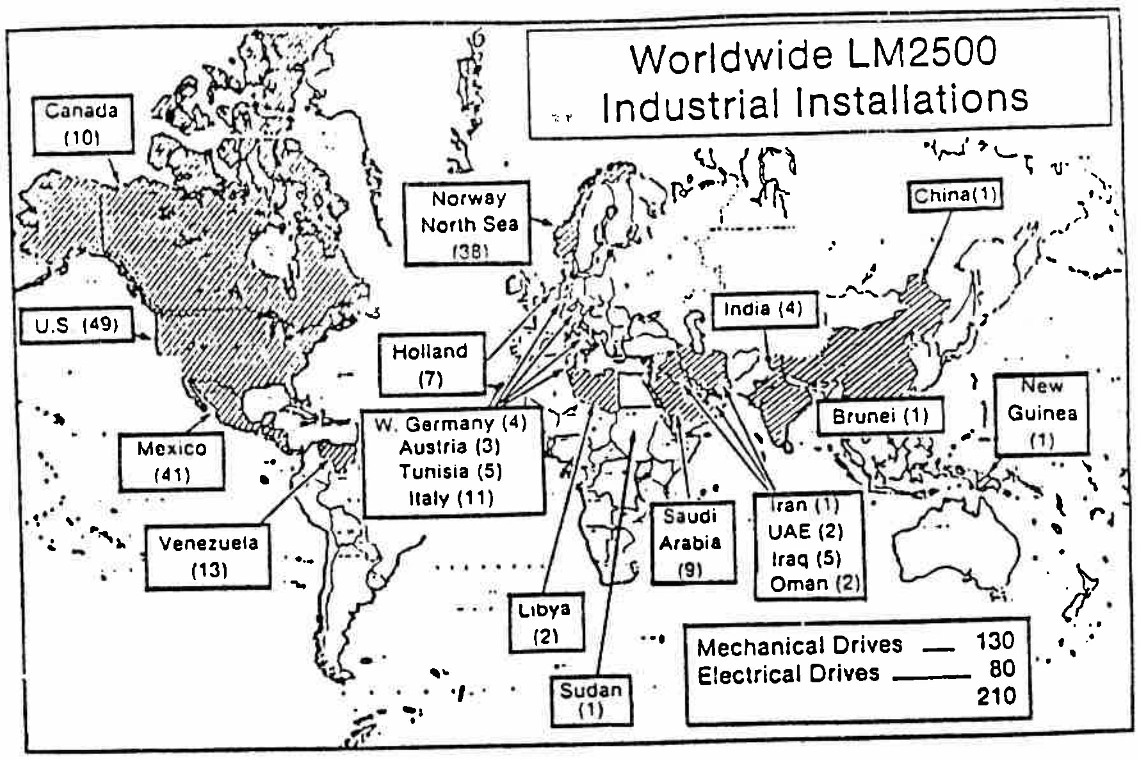

Fig. 5. Current worldwide industrial installations of the General Electric LM-2500 aircraft- derivative gas turbine. (Supplied by the General Electric Company, Cincinnati, Ohio, USA.)

Table 1 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 (Larson et al., 1987). The operating labour estimates are based on employment data for power plants operated by JPS as a function of plant capacity (Montreal, 1985).

CASE STUDY: A JAMAICAN 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 tc/hr 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 tc/hr, which is below its rated capacity of over 200 tc/hr, because of inadequate cane supplies and deteriorating factory equipment (Tate and Lyle, 1984). With World-Bank supported rehabilitations to field irrigation systems, as well as the processing plant, plans are to raise the throughput to 200 tc/hr, 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 2 and discussed in detail elsewhere (Larson et al., 1987, Ogden et al., 1987). 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

TABLE 1 Cogeneration costs assumed in the financial analysis.[a]

Cogeneration System ===>	CEST	GSTIG
Capacity (MW)	27	53
Unit Cost ($/kW)	1560	990
Total Installed Cost (10^6\$)[b]	42	53
Fixed Maintenance (10^3 \$/yr)	660	1300
Variable Maintenance ($/kWh)	0.003	0.001
Number of operating employees	24	55
Labour cost (10^3 \$/yr)	130	300

[a] From Larson et al., 1987

[b] If steam conservation retrofits are made at the factory, the capital cost would increase by $3.1 million (see Table 2)

produce a maximum of about 300 kg/tc of process steam (see Fig. 3 and Note 5), 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 exhaust steam demand to 209 kg/tc, or that available from the mill turbines (Table 2).

Exported-Electricity Price: In principle, the price a utility pays a cogenerator for electricity should reflect the cost of 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 new electricity 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.[8,9]. The cost of operating existing oil-fired plants (O & M and fuel only) in Jamaica is estimated to be 4.5-6.1 ¢/kWh.[10]

Bagasse Costs: During the milling season, a CEST unit would burn unpro-

TABLE 2 Summary of factory end-use scenarios.[a]

FACTORY TYPE EQUIPMENT RETROFITS	COST Thousand 1985 US$	FACTORY ENERGY USE Steam (kg/tc)[b,c] Live	Exhaust	Electricity[d] (kWh/tc)
"Conventional" No retrofits	0	209	374	13.0
"Steam-Conserving"		209	209	13.0
Plate/Gasket Juice Heater	100			
5-effect Fallling Film Evap.	2,400			
Continuous Vacuum Pan	600			
TOTAL	3,100			

a From Larson et al., 1987. See also Ogden et al., 1987.

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

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

d 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 elsewher in this paper, the electrical output of the CEST and GSTIG systems are specified as net of the cogeneration plant.

cessed (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 3.

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

Barbojo, the tops and leaves of the cane, is assumed to be the off-season fuel for the base case, cost estimates for which are given in Table 3. 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 (Phillips, 1986), the Dominican Republic (Vinas, 1987), Mauritius (Deepchand, 1986), The Philippines (Varua, 1986), Thailand (Coovattanachai, 1987) and Florida (Eiland and Clayton, 1982), 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 (Shaw, 1987) has been to focus on developing can e varieties that will retain most of their leaves through harvesting, with the whole cane being transported to a central location where the barbojo and millable cane would be separated.

Initial trial indicate that increased weed growth and decreased soil moisture retention associated with barbojo removal are not serious problems in some cane-growing regions. 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 has yet to be proven commercially viable, plantation fuelwood is considered as the off-season fuel in a second scenario. Experience in tropical regions indicates that the total costs for establishing fuelwood plantations, harvesting, and chipping is in the range of $1.00 to $1.50/GJ (Table 3). For the present study, $1.25/GJ is assumed.

Since barbojo recovery is unproven and "energy plantations" would require several years to establish, a third off-season scenario is considered in which oil is burned during the off-season for the first 5 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 4 are assumed for operation during this five-year period, since these are the prices currently used in JPS projections to the year 2000 (Ashby, 1987).

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 Fig. 6. The cogeneration systems considered here are sized for fuelling with the bagasse available from the processing of 175 tc/hr: 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-

TABLE 3 Levelized fuel assumed for Jamaica case study.

FUEL	PRICE (1985 $/GJ)
BAGASSE	
As delivered from mills, 50% moisture	0.00
Dried to 25% moisture[a]	0.58
Baled, dried to 25% moisture and stored[a]	0.78
Briquetted (12% moisture)[a]	1.16
Pelletized (15% moisture)[a]	2.02
BARBOJO	
Baled, dried to 25% transported and stored[b]	0.97
Briquetted, transported, and stored (12% moisture)[c]	1.35
Pelletized, transported, and stored (15% moisture)[c]	2.21
PLANTATION FUELWOOD	1.00-1.50[d]
RESIDUAL FUEL OIL	
Low	2.90[e]
High	4.00
DISTILLATE FUEL OIL	
Low	5.40[e]
High	7.50
IMPORTED COAL	
Low	1.43[e]
High	2.08[f]

a From Electrobras, 1981

b Estimated in Ronco, 1986. 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% moisture, by the time it is used at the cogeneration plant.

c 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.

d See Table 10 in Larson et al., 1987.

e Currently used in JPS projections to the year 2000.[17]

f Estimated for Jamaica to the year 2000.[17]

TABLE 4 Potential foreign exchange savings to jamaica with alternative cogeneration systems (based on the 1985 level of cane production) by avoiding construction of new coal-fired capacity or by displacing existing oil-fired capacity.[a]

Generating Technology	Potential New Capacity (MW)	Required Capital Investment (Mil. $)	Lifecycle Foreign Exchange For Fuel (Mil. $)[b]	Present Value of Lifcycle FOREIGN EXCHANGE SAVINGS WITH COGENERATION over Coal/Oil Firing[c] (Mil. $)	(\$/MWh)
1. CEST COGEN[d]	79	132	0		
vs. New coal-Steam[e]					
Coal @ \$1.43/GJ	88	116	70	54	3.54
Caol @ \$2.08/GJ	88	116	102	86	5.64
Vs. Existing Oil-Steam[f]					
Oil @ \$2.9/GJ	0	0	172	not applicable[g]	
Oil @ \$3.2/GJ	0	0	190	58	3.81
Oil @ \$4.0/GJ	0	0	237	92	6.89
2. GSTIG COGEN[h]	153	160	0		
vs. New coal-Steam[e]					
Coal @ \$1.43/GJ	172	226	138	204	6.84
Caol @ \$2.08/GJ	172	226	200	266	8.92
Vs. Existing Oil-Steam[f]					
Oil @ \$2.9/GJ	0	0	337	177	5.94
Oil @ \$3.2/GJ	0	0	372	212	7.11
Oil @ \$4.0/GJ	0	0	464	304	10.2

[a] 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.

[b] For a 12% discount rate and a 30-year lifecycle.

[c] For this analysis, all of the capital is assumed to be foreign exchange.

[d] Assuming all of the capacity is installed at a cost of \$1671/kW, which includes factory retrofits for a "steam-conserving" factory, and a calculated capacity factor of 73%.

[e] See footnote 8 for assumptions associated with the cost of electricy from the coal-steam plant.

[f] See footnote 10 for assumptions associated with the cost of electricy from the oil-steam plant.

[g] 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 pil-fired plants would equal the total generating cost for the CEST (\$0.048/kWh).

[h] Assuming all of the capacity is installed at a cost of \$1048/kW, which includes factory retrofits for a "steam-conserving" factory, and a calculated capacity factor of 74%.

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 (Fig. 6), since the extra investment costs (Table 2) would offset the extra electricity revenues.

Investing in the GSTIG system (fuelled by briquetted bagasse and barbojo[11]) and "steam-conserving" retrofits would provide an estimated ROR of 18-23%, and exports of electricity would be about double that for the CEST (Fig. 6)[12]

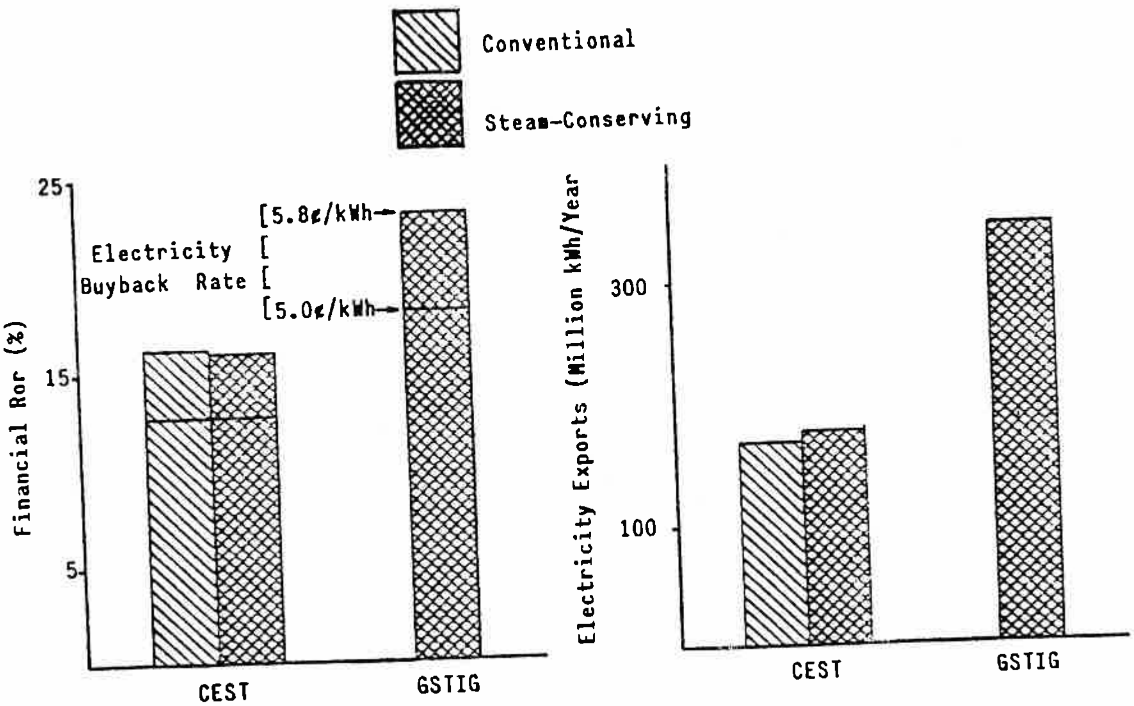

Fig. 6. Financial rates of return and annual electricity exports for cogeneration and process-equipment investments at "conventional" and "steam-conserving" described in Table 2. Table 1 gives cost assumptions for the cogeneration facilities. A thirty-year economic life is assumed in all calculations.

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 buy-back 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%.

If plantation fuelwood were used as the off-season fuel, the RORs for both the CEST and GSTIG would be comparable to those for the base case shown in Fig. 6, since the off-season fuel costs would be comparable. The total fuelwood plantation area required would represent 30-40% of the sugar cane land area[13], but the GSTIG would export about twice as much electricity per hectare of plantation as the CEST. New permanent employment associated with maintenance of the plantations would represent about 30% of the estimated direct employment associated with Monymusk today, and a still larger number of temporary jobs would be created in establishing the plantations.

For the scenarios in which oil is burned during the first 5 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.[14]

Results for Small Installations

The average cane-processing capacity of sugar factories in Jamaica and many other countries is lower than 175 tc/hr. Since there are scale economies associated with both the CEST and GSTIG technologies (see Fig. 4), the ROR would decrease in both cases for cogeneration investments at small factories. However, because of its weaker scale economies, the financial advantage of the GSTIG relative to the CEST would increase with decreasing size. For a "steam-conserving" factory processing about 20 tc/hr, the ROR would be 9-13% for a 5-MW GSTIG unit (fuelled by briquetted cane residues) and 3-5% for a 3-MW CEST (using less-processed cane residues) (Larson et al., 1987).

CASE STUDY: NATIONAL 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 1) would be far in excess of investments to which sugar producers are accustomed. In 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 (Fig. 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 track evolving 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. If plantation fuelwood were the off-season fuel, generating costs would be 4.0 ¢/kWh for the GSTIG and 5.1 ¢/kWh for the CEST. In the scenarios involving oil the costs would be about 5.2 ¢/kWh for the GSTIG and 5.4 ¢/kWh for the CEST. These cogeneration costs are compared in Fig. 7 to 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 Note 8). In all cases shown in Fig. 7, 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 Fig. 7 to the operating cost of existing oil-fired power plants, which would range from 4.5 to 6.1 ¢/kWh (see Note 10). 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. Under the conditions, it would be economically worthwhile to scrap existing oil-fired plants and replace them with new GSTIG facilities.

If Jamaica's total resource of cane residues were to be exploited for power, some existing oil-fired generating capacity could be retired, new central-station powerplant construction could be deferred for many years or perhaps decades, and substantial foreign exchange would be saved. A typical 1980s 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 1,437 million kWh in 1985. If GSTIG generated 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 4). If cogenerated power displaced electricity from existing oil-fired units, up to \$300 million might be saved (Table 4). Per kWh cogenerated, the savings with GSTIG would be 50-90% greater than with CEST.

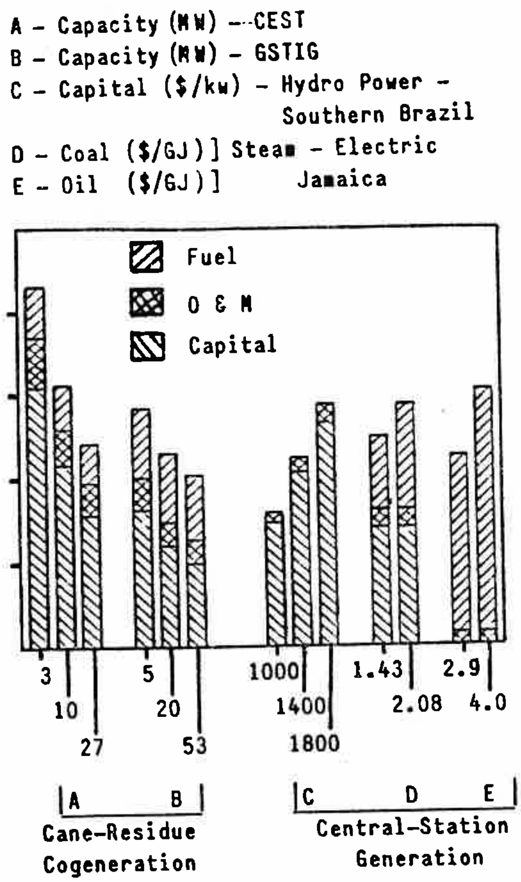

Fig. 7. Estimated levelized cost of generating exportable electricity with CEST and GSTIG cogeneration systems at a "steam-conservation" sugar factory and for three central-station alternatives.[1] Total costs are shown for a new 61-MW coal-steam plant in Jamaica and new hydro plants supplying power to Southeast Brazil. Also shown is the cost of operating existing oil-steam plants in Jamaica. The three cogeneration cases correspond to the scenarios described in the text.

Southeast Brazilian Context

Southeast Brazil, where most of Brazil's sugar cane grows and which includes the heavily industrialized state of Sao Paulo, provides an interesting contrast to Jamaica, because it is a cane-producing region which relies heavily on hydropower, a much less costly electricity source than most alternatives. With electricity demand in Sao Paulo growing at 8-10% per year (Conselho, 1986), the installation of new hydro capacity is under consideration. Since all of the economical hydro potential has already been exploited in the South, however, new plants would be built in the Amazon, with transmission lines connecting them to

Sao Paulo (Correa, 1987). Electricity from such facilities is estimated to cost from 3.2 to 5.8 ¢/kWh, depending primarily on the siting of the facility (Fig. 7).

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 Sao 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 supplies. By contrast, only the larger CEST units would be competitive and then only with the higher-cost hydro (Fig. 7).

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. For example, the capital charges for GSTIG power would be 50 to 80% of those for hydro capacity costing $1400/kW (Fig. 7). 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 electric utilities if hydro 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 hydropower "trough", (Fig. 8), thus making greater use of the installed hydroelectric capacity. Furthermore, since the GSTIGs would have the capability to operate on oil in the off-season, a larger risk of a rain-short year could be designed into new hydro facilities, resulting in still lower capital charges for hydropower.

IMPLICATIONS

The introduction of GSTIG units worldwide 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 5). Based on an extrapolation of the results for Jamaica, some 300 billion (10^9) kWh of electricity could be produced at the 1985 level of cane production (Table 6). This is more than 1/4 of the electricity generated by utilities in these countries in 1982, and is comparable to the level of electricity generated with oil.

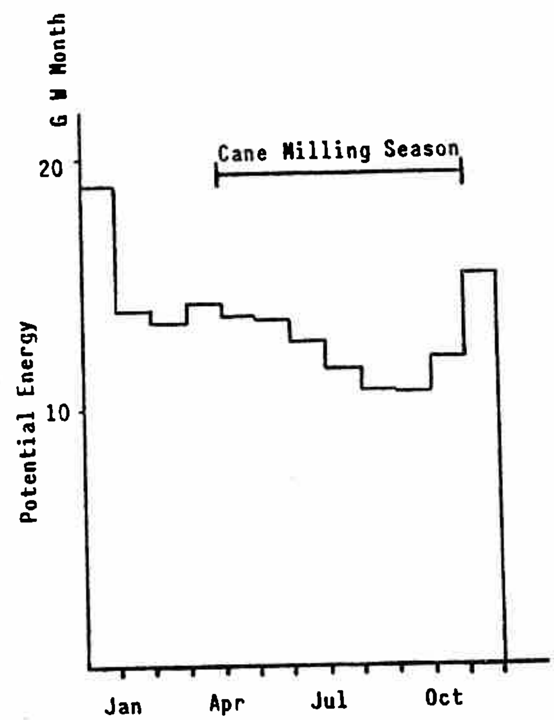

Fig. 8. The current hydro-electricity supply "trough" and the sugar cane milling season in the state of Sao Paulo, Brazil.

TABLE 5. Estimated potential worldwide GSTIG generating capacity at sugar factories with the 1985 level of sugar cane production.[a,b]

Region	Potential Electrical Capacity (MW)
South America	17,800[c]
Asia	14,000
Central America	10,100
Africa	4,900
Oceania	2,700
United States	1,900
Europe	200
TOTAL	51,600

a Sugar cane production, assuming ten tonnes of cane are required to produce one tonne of sugar. Sugar production from ISO, 1986.

b 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.

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

A global transition to GSTIG cogeneration, while attractive, offers challenges for both the sugar and electric utility industries. 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 or "energy plantations" would be desirable to supply fuel for the off-season. Since investments in a cogeneration plant would typically be large compared to 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 (Brown, 1987) would insure 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 (Larson et al., 1987). Although the fuel-alcohol industry is developed on a large scale today only in Brazil, this situation may change, if, as expected[15], oil prices rise considerably in the next 10-15 years. In light of the favourable projected economics of GSTIG cogeneration, a co-product strategy with GSTIG-electricity could

TABLE 6 GSTIG electricity generating potential using the 1985 level of cane production (A) and the actual total electric utility generation in 1982 (B) in developing countries. Number are given in 10^9 kWh [a]

	A	B		A	B	A	B
ASIA						89	599
India	31.6	129.5	Iran	0.90	17.5		
China	19.0	327.7	Vietnam	0.81	1.69		
Thailand	10.8	16.2	Burma	0.45	1.52		
Indonesia	7.6	11.9	Bangladesh	0.42	2.98		
Philippines	7.4	17.4	Malaysia	0.32	11.1		
Pakistan	6.4	14.9	Nepal	0.12	0.284		
Taiwan	3.4	45.0	Sri Lanka	0.07	2.07		
CENTRAL AMERICA						65	100
Cuba	35.5	10.8	Jamaica	0.94	1.30		
Mexico	15.7	73.2	Panama	0.72	2.71		
Dominican Rep	4.2	2.38	Belize	0.49	0.065		
Guatemala	2.3	1.42	Barbados	0.45	0.339		
El Salvador	1.2	1.45	Trinidad & Tob	0.36	2.30		
Nicaragua	1.1	0.945	Haiti	0.23	0.352		
Honduras	1.0	1.04	St. Chris.- Nevis	0.12	na		
Costa Rica	1.0	2.42					
SOUTH AMERICA						117	257
Brazil	95.0	143.6	Guyana	1.1	0.255		
Colombia	6.1	21.3	Bolivia	0.78	1.40		
Argentina	5.5	36.2	Paraguay	0.36	0.569		
Peru	3.3	7.25	Uraguay	0.23	3.47		
Venezuela	2.1	39.0	Suriname	0.05	0.175		
Ecuador	1.3	3.09					
AFRICA						32	167
South Africa	11.4	109.0	Mozambique	0.26	3.25		
Egypt	3.7	17.2	Somalia	0.24	0.075		
Mauritius	3.1	0.320	Nigeria	0.23	7.45		
Zimbabwe	2.1	4.16	Angola	0.23	1.46		
Sudan	2.0	0.910	Uganda	0.15	0.569		
Swaziland	1.8	0.075	Congo	0.11	0.195		
Kenya	1.6	1.73	Mali	0.09	0.080		
Ethiopia	0.87	0.618	Gabon	0.05	0.530		
Malawi	0.69	0.410	Burkina Faso	0.05	0.123		
Zambia	0.64	10.3	Chad	0.04	0.065		
Ivory Coast	0.57	1.94	Guinea	0.02	0.143		
Tanzania	0.47	0.720	Sierra Leone	0.02	0.136		
Madagascar	0.45	0.342	Benin	0.02	0.016		
Cameroon	0.32	2.15	Liberia	0.01	0.389		
Zaire	0.30	1.48	Rwanda	0.01	0.066		
Senegal	0.30	0.631					
OCEANIA						2	1
Fiji	1.6	0.241	Pap. N. Guinea	0.13	0.441		
ALL SUGAR-PRODUCING DEVELOPING COUNTRIES						304	1,124

[a] From Larson et al., 1987.

make alcohol production economically attractive at lower oil prices than otherwise (Larson et al., 1987), a possibility that warrants a detailed assessment.[16]

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:

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

- 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.

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

- 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 in from centralized facilities) continue to produce power.

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

- 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-1990s.

- 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.

Introduced for initial operation on the biomass already available in the sugar cane-processing industries, GSTIG systems might motivate subsequent wider applications using other biomass forms, including fuelwood from "energy plantations".

- The higher efficiency and lower capital cost of GSTIG relative to CEST would make fuelwood more valuable for power generation than would be the case for existing wood-burning power generating technology, thus making fuelwood plantations a more attractive investment opportunity.

- GSTIG systems would be used largely in rural areas of developing countries, where they might help generate greater employment opportunities by increasing the value of the agricultural products, and hence the level of investment in the agricultural sector.

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NOTES:

1 Note that in all cases in Fig. 1, for ease of comparison, the electricity production is referenced to the cane processed during the milling season.

2 With steam injection, 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 (Larson et al., 1987).

3 PURPA requires electric utilities to purchase cogenerated electricity at a price equal to the cost the utility could avoid by not having to otherwise supply that electricity.

4 In a gas-turbine steam-turbine combined cycle powerplant, 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 used in combined cycles.

5 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 20-0/0 of the total steam production, which is based on the steam requirements when gasifying coal in this type of gasifier (Corman, 1986). The gasification steam required with biomass may be lower, although sufficient testing with biomass feedstocks has not been carried out to determine this. An 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 (Bellin et al., 1985).

6 The United States' GNP deflator has been used to express all costs in this paper in constant 1985 US dollars.

7 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 20 years, with total maintenance costs averaging $0.002-$0.003/kWh. (Larson and Williams, 1986).

8 Assuming an installed cost of $1316/kW (which includes a proportion 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 $0.003/kWh, a discount rate of 12%, and a 30-year economic life (Montreal, 1985). Assumed coal costs are given in Table 3.

9 Generating costs estimated elsewhere (Ronco Inc., 1986) for Jamaica are: 8.3 ¢/kWh for a new oil-fired steam-electric plant, 6.6 ¢/kWh for a new coal-fired steam-electric plant, and 8.7 ¢/kWh for a new oil-fired gas turbine plant.

10 Assuming a heat rate of 14,500 kJ/kWh and an O & M cost of $0.003/kWh (Montreal, 1985). The assumed costs of residual fuel oil are given in Table 3.

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