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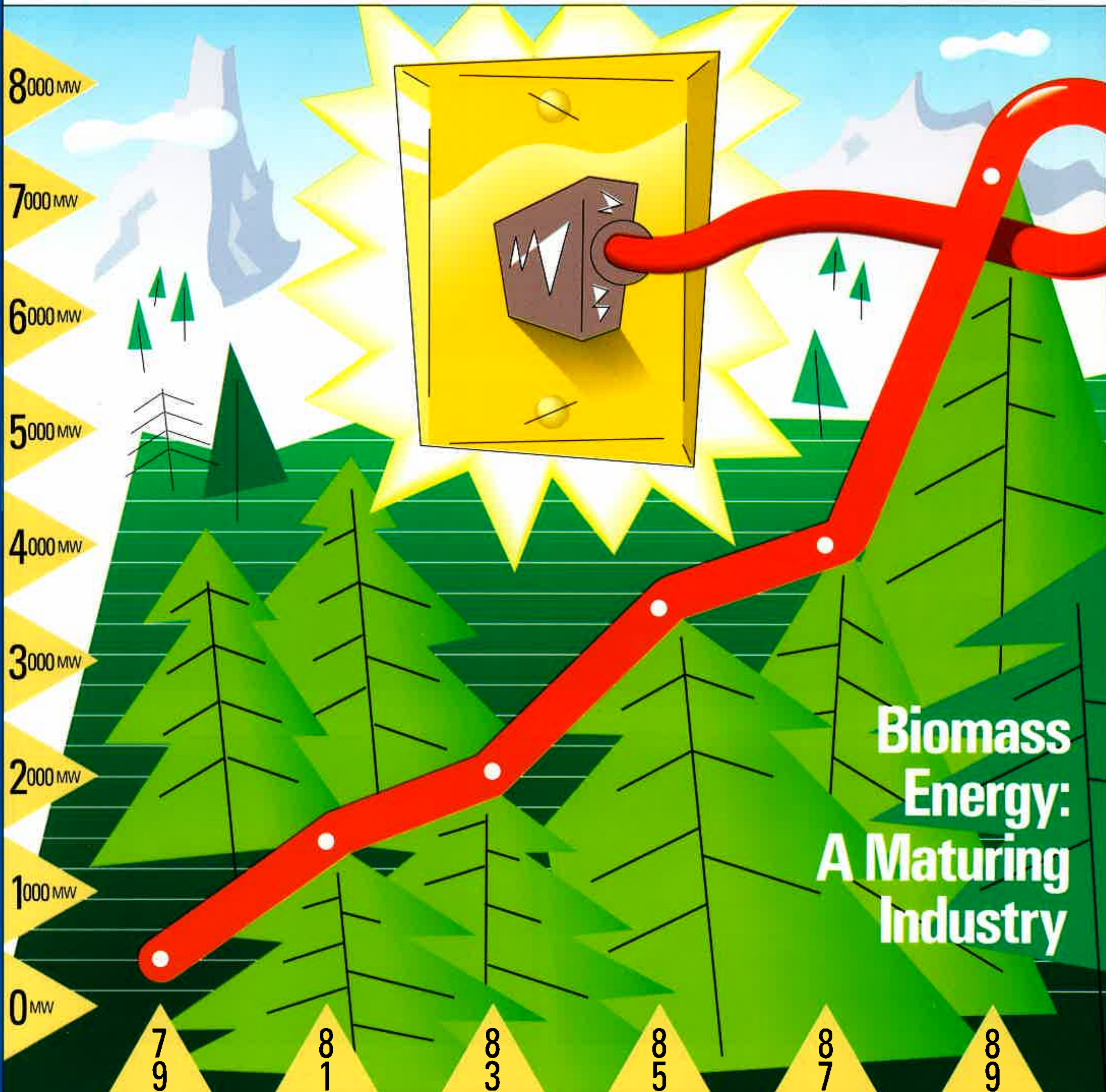

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Biomass-Fired Steam-Injected Gas Turbine Cogeneration

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(This article is adapted from a paper presented at the 1988 ASME Cogen-Turbo Symposium, Montreux, Switzerland.)

Introduction

The gas turbine has been limited in cogeneration applications to natural gas or distillate fuel, but the technology is also a good candidate for biomass cogeneration. Because biomass—wood, wood waste, crop-processing residues, refuse derived fuel (rdf)—is a widely distributed energy resource, the size of a power plant that can be fueled by biomass at any one site is small (50 MW or less). At such sizes, gas turbines are thermodynamically more efficient cogenerators than steam turbines, and their unit costs are lower and less sensitive to scale than those for steam turbines or gas turbine-steam turbine combined cycles.

Because of its low efficiency in producing only power and its poor part-load efficiency, the simple-cycle gas turbine is not well matched to the many potential biomass cogeneration applications. However, the steam-injected gas turbine is a good candidate for such applications if the electricity produced in excess of on-site needs can be marketed, e.g., sold to the utility.

Steam injection for power and efficiency augmentation is a modification of simple-cycle aeroderivative gas turbines that has proven its commercial viability in applications with natural gas as fuel: 8 steam-injected gas turbines (STIGs) based on the Allison 501-KH, 7 based on the General Electric LM-2500, and 4 based on the LM5000 have been purchased since STIGs were introduced in the mid-1980s. In a STIG cogeneration system, steam is produced in an exhaust heat recovery steam generator (HRSG), and steam not needed to meet the process heat demand is injected into the combustor and points downstream to augment power output and the efficiency of power generation. Table 1 shows the estimated performance of the three commercial STIG systems, as well as two units which may become available in the next few years. The most efficient of all of these, based on the General Electric LM-5000, produces 33 MW at 33% efficiency without steam injection and 51.4 MW at 40% efficiency with full steam injection. (Note: Higher heating values are used for fuels in this paper.)

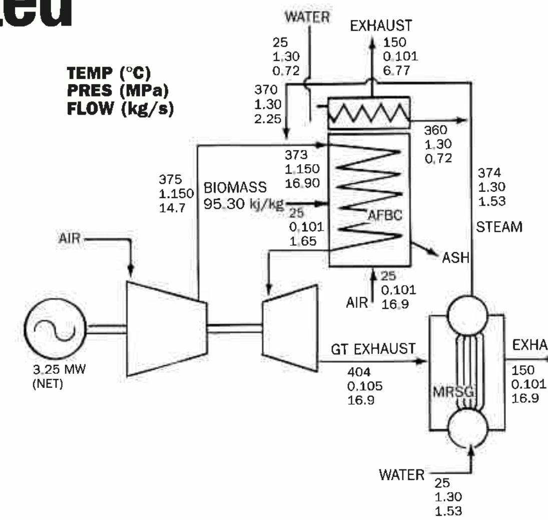

Figure 1. *Calculated energy and mass flows in an indirectly fired STIG unit based on the Allison 501-K gas turbine*

The success of natural gas-fired STIGs in the United States together with uncertainties in the long-term availability and price of natural gas has prompted development work of STIGs fueled by coal and biomass. In this paper, we assess the status, performance, cost and over-

Table 1
Estimated performance of steam-injected turbines operating with natural gas.

Engine Characteristics			Performance Estimates Cogeneration				Power Only	
	TIT	Comp	Elec		Steam[c]		Elec	
Model[a]	°C	Ratio	MW	%HHV	kg/hr	%HHV	MW	%HHV
LM-5000	1211	25.3	33.1	33.0	47,700	37.1	51.4	40.0
LM-2500	1211	18.5	21.2	33.0	34,500	41.9	26.3	36.0
501K	982	9.3	3.3	24.0	9,850	55.9	5.5	35.0
Projected								
LM-1600	1241	22.5	12.8	31.3	21,800	41.6	17.8	36.5
GE-38[b]	1204	23.0	3.4	30.6	5,700	40.0	5.3	37.1

[a] The 501K is made by Detroit Diesel Allison. Other are made by General Electric.
[b] The GE-38 will be introduced in the early 1990s to take the place of the existing, less efficient, more costly LM-500.
[c] Steam condition is 2 MPa, 316 C. Feedwater at 60 C.

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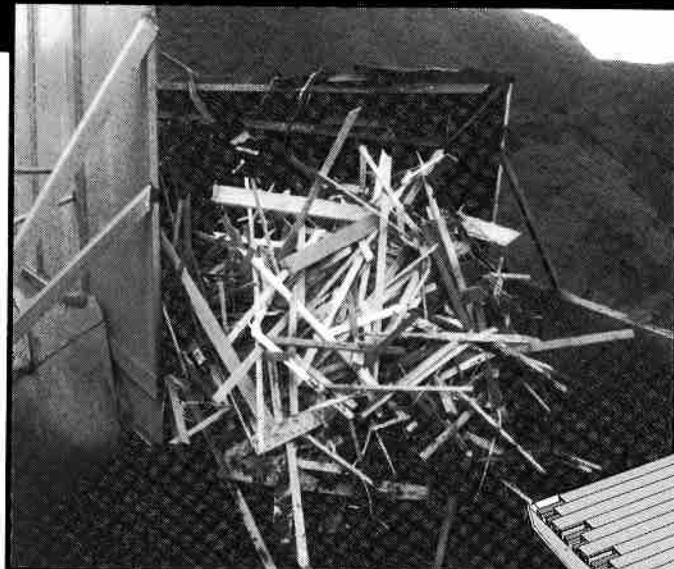

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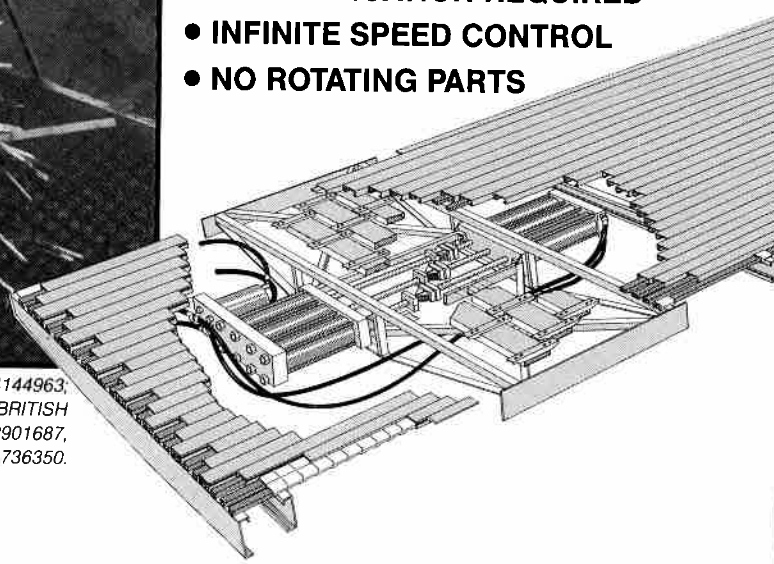

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all economics of alternative biomass-fired STIG cogeneration technologies.

Biomass-Fired STIGs

Three biomass-fired STIG concepts are described here. To provide perspective, comparisons are made, where appropriate, to condensing-extraction steam turbine (CEST) systems, the state-of-the-art in biomass-fired power generation.

Directly-Fired STIG

In a STIG fired directly with biomass, compressor air is diverted to a high-pressure combustor where biomass is burned. After passing through particulate-removing cyclones, the hot gases are ducted back to the turbine. The hot turbine exhaust gases raise steam in a HRSG for process use or injection.

A modest development effort is ongoing for gas turbines fired directly with biomass. A 3 MW Allison 501-K, coupled to a sawdust-fired dry-ash combustor, is presently undergoing trial operation at Red Boiling Springs, Tennessee in the US, primarily to determine the extent of clean-up of the hot combustion products required to insure adequate turbine life. The system has operated successfully at turbine inlet temperatures less than 790° C, but has encountered solids deposition on the turbine blades at higher temperatures. If successfully developed, this system would be attractive because it is projected to cost about $500/kW and be simpler in construction than the other biomass-fired gas turbine options.

Given the limited success in testing to date, the commercial viability of this system has yet to be established. For this reason, detailed performance and cost estimates are not included here.

Indirectly-Fired STIG

Status. In a STIG fired indirectly with biomass (IFSTIG), the fuel is burned in a atmospheric-pressure combustor, and heat is transferred through a heat exchanger (air heater) to the compressor exhaust air. The turbine exhaust heat is used to raise steam for process use or injection. Additional steam can be generated using the combustor exhaust gases. Most development work on indirectly-fired gas turbine systems has been targeted at coal applications, but there are no apparent difficulties in using biomass. In fact, IFSTIG systems may

Table 2

Estimated performance of indirectly-fired steam-injected gas turbine (IFSTIG), gasifier steam-injected gas turbine (GSTIG), and condensing-extraction steam turbine (CEST) systems

Prime Mover[a]	Cogeneration Elec MW	Cogeneration Elec %HHV	Cogeneration Steam[b] kg/hr	Cogeneration Steam[b] %HHV	Power Only Elec MW	Power Only Elec %HHV
IFSTIG[c]						
501-K	1.68	13.3	6,950	39.5	3.24	20.6
GT-35C	12.7	17.5	32,280	32.0	21.4	24.5
GSTIG						
LM-5000[d]	39	28.6	47,700	27.3	53	32.5
LM-1600[e]	15	27.1	21,800	30.7	20	30.8
GE-38[e]	4	26.5	5,700	29.5	5.4	30.1
CEST[f]						
Generic	17.5	13.0	65,550	35.9	27.0	20.3
Generic	6.1	11.4	26,440	36.4	10.0	17.8
Generic	1.8	10.1	9,010	37.2	3.0	15.7

[a] For the IFSTIG and CEST, the fuel is 50% mc biomass. For the GSTIG, the fuel is 15% mc biomass. If 15% mc fuel were used in the IFSTIG and CEST, electrical efficiencies would be improved by about 20%.

[b] Steam at 1.3 MPa, 330° C for the IFSTIG; 2 MPa, 316° C for the GSTIG; and 2 MPa, 250° C for the CEST.

[c] The following engine characteristics were assumed for modeling purposes:

	501-K	GT35C
Turbine Inlet Temperature (°C)	815	815
Simple-cycle compression ratio	9.3	12.5
Compressor inlet mass flow (kg/s)	14.7	90.3
Average compressor adiabatic eff.	0.83	0.84
Average turbine adiabatic eff.	0.87	0.945
Average gear box/generator eff.	0.93	0.93

[d] Based on Table 3.

[e] Obtained by comparing the performance of the LM-5000 on natural gas (Table 1) to that on biomass (this table) and applying the percentage differences in output and efficiency to the projected performance of the LM-1600 and GE-38 on natural gas (Table 1).

[f] The performance of the 27-MW unit is estimated based on a 6.3 MPa, 482 C system fueled by 50% mc biomass. For the smaller systems, efficiency in the power-only mode is estimated from E-13.93x(MW)0.107, where E is in percent. Other performance figures were obtained by extrapolating those for the 27-MW system.

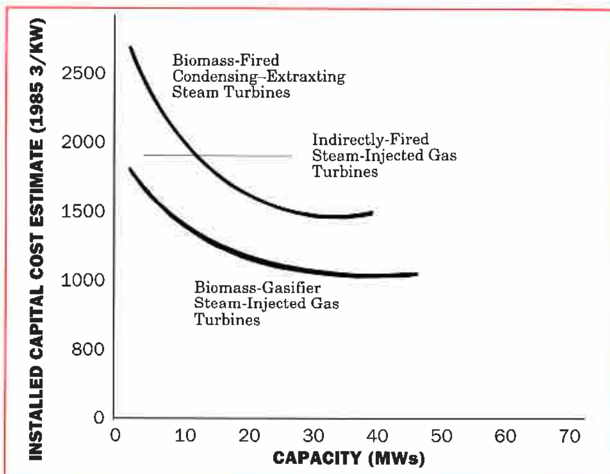

***Figure 2.** Estimated unit installed capital costs for biomass-fired condensing-extraction steam turbine and steam-injected gas turbine cogeneration plants.*

be considered commercially ready for biomass applications, since several vendors now offer the major system components.

Development work on indirectly-fired systems has concentrated on increasing the heat transfer efficiency and the temperature limit of air heaters. The most promising combustion technology is the atmospheric fluidized-bed combustor (AFBC), of which there are several varieties, including bubbling-, circulating- and multiple-bed systems. AFBC boilers are already well-established in applications with coal and high moisture biomass fuels, but there are no commercially operating AFBC-IFSTIG systems. Prototype AFBCs with air heaters for gas turbine applications have been tested by several manufacturers, and a 10 MW petroleum-coke-burning commercial demonstration plant has operated successfully for approximately 2000 hours in Torrence, California.

Performance. The performance of biomass-IFSTIGs based on Allison 501-K and ASEA-STAL GT-35C gas turbines were estimated using a computer model developed for this purpose. Both systems were modeled with a turbine inlet temperature of 815° C, a limit imposed by material constraints of the air heater tubes. A 3-zone bubbling-bed AFBC/air-heater/boiler and a single-pressure HRSG (with blow-down neglected) were included in the model. (Two boilers were included in the model to simplify calculations. In practice, the two boilers would probably be combined into a single unit.) The fuel was a 50% moisture content (mc) biomass having a heating value of 9,530 kJ/kg. The dry composition on a mass basis was representative of sugar cane bagasse (the fiber residue of cane milling): 46% oxygen, 44% carbon, 6% hydrogen, and 4% ash. Detailed energy and mass balances were generated for a number of cycle configurations, as illustrated in Fig. 1 for the 501-K IFSTIG.

The 501-K with full steam injection (Table 2) produced about 3.2 MW of power at 21% efficiency. A natural-gas burning STIG (Table 1) produces about 5.5 MW at 35% efficiency. The reduced performance of the IFSTIG is due to the turbine inlet temperature being constrained far below its rated value of 980° C and to the high moisture content of the fuel. In simple-cycle operation, the power

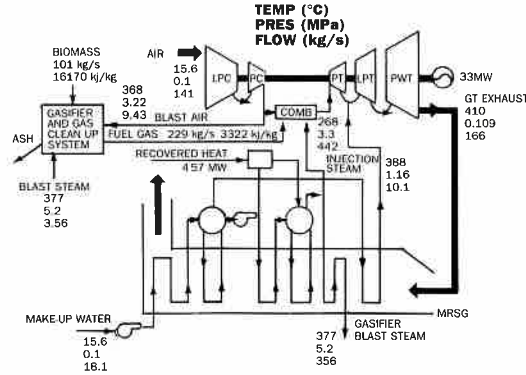

Figure 3. *Biomass-gasifier steam-injected gas turbine cycle showing preliminary energy and mass balances for a system based on the GE LM-5000 gas turbine. The energy flow marked Recovered Heat accounts for feedwater preheating in the gasifier cooling jacket and in a air cooler preceding the gasifier boost compressor.*

Table 3
Performance estimates for coal-GSTIG and biomass-GSTIG units based on GE LM-5000 STIGs and Lurgi Mark-IV gasifiers

		Coal	Biomass[a]
Gasifier			
Feedstock			
Type		Ill. #6	pellet
Higher heating value (kJ/kg)		25,011	16,166
Flow rate (tons/hr)		20.4	36.4
Gas Production/a			
Composition (Mole %)[b]	N2	31.6	27.13
	CO2	14.19	12.05
	CO	4.79	15.72
	H2	18.54	11.90
	CH4	3.21	4.65
	H2O	26.98	27.81
	C2H4[c]	0.47	0.71
	Ar	0.37	—
	NH3	0.20	—
Higher heating value (kJ/kg)		4,565	5,522
Lower heating value (kJ/kg)		4,055	5,099
Temperature (° C)		640	600
Flow rate (tons/hr)		94.9	82.3
Gasification Efficiency (HHV)			
Chemical energy out/			
Feedstock energy in		0.849	0.772
Steam-Injected Gas Turbine/HRSG			
Fuel Input			
Higher heating value (kJ/kg)		4,565	5,522
Flow rate (tons/hr)		94.9	82.3
Electrical Output			
Gross output (MW)		52.41	55.1
Balance of plant demand (MW)		1.917	2.0
STIG Cycle Efficiency (HHV)			
Net electricity out/Chemical			
energy in gasified feedstock		0.419	0.421
Overall Efficiency (HHV)		**0.356**	**0.325**
Net Electrical Output (MW)		**50.49**	**53.1**

[a] Biomass figures are estimated based on results of GE wood-pellet gasification tests, and assuming the major biomass components (percent mass dry basis) are 45% carbon, 46% oxygen, and 6% hydrogen.
[b] At inlet to combustor.
[c] Represents tars, oils, and phenols.

output and efficiency are significantly lower.

The GT-35C IFSTIG with full steam injection produces about 21 MW at 25% efficiency. A natural-gas burning STIG would produce about 24 MW at 35% efficiency. The performance penalty is less severe than with the 501-K because the rated turbine inlet temperature for the GT-35C, 825° C, is much closer to the temperature limit for indirectly-fired systems.

Despite the reduced efficiencies of the gas turbine with indirect firing, IFSTIG systems would produce electricity 25-30% more efficiently than comparably-sized CEST systems (Table 2).

Table 4
Capital and annual O&M cost assumptions

PRIME MOVER	Capacity (MW)	Installed Cost ($/kW)	Maintenance Fixed (103$)	Maintenance Var. ($/kWh)	Labor (103$)
Condensing-Extraction Steam Turbines					
Generic	27.0	1556	664.2	0.003	129.6
Generic	10.0	2096	246.0	0.003	97.2
Generic	3.0	3008	73.8	0.003	97.2
Gasifier-Steam-Injected Gas Turbines					
GE-LM-5000	53.0	990	1304	0.001	297.0
GE-LM-1600	20.0	1230	492.0	0.001	108.0
GE GE-38	5.4	1650	133.0	0.00	197.2

Capital Costs. The installed unit capital cost for IFSTIG systems is estimated to be about $1900/kW for both the 501-K and GT-35C, based on previous detailed engineering studies and discussions with industry experts. The high cost can be attributed primarily to the large combustor and air heater surface area required. There are probably no significant scale economicies with IFSTIGs, since the fuel-handling and combustion equipment for larger units would generally require field, rather than shop fabrication, while smaller shop-fabricated systems would suffer some penalty in efficiency. The IFSTIGs would probably be competitive on a capital-cost basis with small (less than 15 MW) CEST cogeneration systems (Fig. 2).

Gasifier-STIG

Status. In a gasifier-STIG (GSTIG), biomass is converted into gas in a pressurized gasifier fusing some air from the compressor and some steam from the HRSG before entering the combustor (Fig. 3). A GSTIG system would be much more efficient than an IFSTIG system because gasification losses would be more than compensated for by the efficiency gains arising from the much higher turbine inlet temperature possible with direct firing. The cost of the AFBC and heat exchanger would also be eliminated, although these savings would be partially offset by the added cost of a gasifier.

The technical feasibility of operating gas turbines on gas derived from coal has been demonstrated at the 100-MW Cool Water combined-cycle power plant in California. At Cool Water, gas produced from coal in an oxygen gasifier is cooled and scrubbed of sulfur before it is burned in the combustor. As part of a U.S. Department of Energy (US/DOE) effort to improve on the efficiency and capital cost of the Cool Water technology, General Electric (GE) examined alternative gasifier/gas turbine combinations and found that marrying an air-blown Lurgi fixed-bed, dry-ash gasifier with hot-gas clean-up to a STIG unit was especially promising.

Three major technical issues were addressed in the GE work: combustibility of low-Btu gas; hot particulate clean up with cyclones; and hot sulfur removal. The analysis and supporting experiments indicated that combustors for aeroderivative turbines could be modified to burn gas with a heating value as low as 3.0 MJ/m3 (104 Btu/scf). In addition, measurements indicated that cyclones following a fixed-bed gasifier were sufficient to reduce particulate loadings to well within gas turbine specifications (Fig. 4). The major uncertainty regarding the proposed coal-GSTIG is the commercial viability of the hot-gas sulfur removal system, which GE proposed to demonstrate at commercial-scale within a year's time, 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. The entire scale-up/demonstration effort was shelved, however, when the US/DOE elected to fund an alternative "clean coal" project.

The coal-GSTIG technology is largely transferable to systems based on biomass, but the commercialization of biomass-GSTIG systems would probably require less developmental effort. The higher reactivity of biomass makes it inherently easier to gasify than coal. Furthermore, most biomass contains

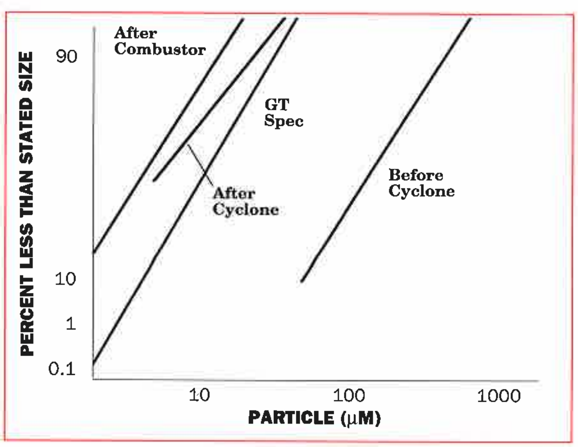

Figure 4. *Particulate loadings in coal-gas before and after cyclones (installed after a fixed-bed gasifier) and after the gas turbine combustor, as measured at pilot-scale by General Electric. Also shown are specifications developed by GE in the late 1970s as part of a US/DOE supported program in pressurized-fluidized bed coal combustion for gas turbine applications.*

virtually no sulfur, so that no new sulfur-removal technology would need to be proven. Moreover, the scale of demonstration biomass-GSTIG plants would be comparable to that of commercial plants, obviating the need for significant scale-up development work. Thus, by "piggy-backing" on coal-GSTIG work, the commercialization of the biomass-GSTIG could be accomplished in less than 5 years.

Performance. Engineers at GE have made preliminary estimates of the performance of biomass-GSTIG systems based on the use of empirical biomass gasification data in a detailed computer model of the LM-5000 STIG fired with low-BTU gas, which was used previously for coal-GSTIG analyses. Table 3 shows the estimated performance of the coal-fired system, based on a Lurgi Mark IV fixed-bed gasifier and LM-5000 STIG, and preliminary estimates for a similar system fired with 15% mc biomass. Calculated system energy and mass flows for the biomass-GSTIG are shown in Fig. 3.

Table 3 indicates that the biomass-GSTIG would produce a comparable amount of power (53 MW) to the coal-GSTIG, but the overall system efficiency would be 32.5%, about 10% less than with coal. The difference is due to an assumed lower gasification efficiency for biomass. Because only limited experiemental data were available (from gasification experiments conducted at GE on wood pellets) GE engineers made a conservative estimate of the gasification efficiency. However, there is no obvious reason why the gasification efficiency of biomass would not be as high as the better-documented estimate for coal.

The estimated performance characteristics of the LM-5000 biomass-GSTIG in cogeneration and power-only modes of operation are summarized in Table 2. These results have been extrapolated to estimate the performance of smaller systems, since many potential biomass applications are relatively small. Throughout the size range from 5 to 50 MW, the biomass-GSTIG systems would produce electricity far more efficiently than CEST or IFSTIG systems (Table 2).

Capital Costs. The installed capital cost for a 53-MW LM-5000 biomass-GSTIG, $990/kW, was estimated from a detailed cost estimate for a coal-GSTIG by substracting the costs associated with chemical sulfur removal, which represents about 20% of the total. The cost estimate for a 5-MW GE-38 system, $1,650/kW, was developed based on discussions with GE engineers. The cost estimates for the 5 and 53 MW systems were used to develop estimates for intermediate-sized plants.

The estimated unit costs for biomass-GSTIG systems are lower than for either IFSTIG or CEST systems (Fig. 2). In addition, the scale economies associated with GSTIG are weaker than for CEST units: even in the larger GSTIG plants it is expected that shop fabrication could be utilized extensively, since the fuel conversion system is pressurized, making the overall system quite compact and readily transportable.

Maintenance

For base-load applications of natural gas-fired aeroderivative gas turbines, maintenance costs have been reported in the range of 0.2-0.3¢/kWh. Such relatively low costs are a result of maintenance programs unique to aeroderivative turbines: minor on-site maintenance is facilitated by the modular nature of the units; major maintenance is done off-site, while a replacement from a lease-engine pool continues to produce power. Gas turbine availabilities in excess of 90% are typically guaranteed by vendors under such maintenance agreements.

To estimate the fixed and variable maintenance costs for IFSTIG, GSTIG, and condensing steam turbine cogeneration systems, several previous studies were reviewed. The costs are similar for the CEST and IFSTIG plants, because both systems require the processing of large volumes of fuel through similar combustion and heat exchanger systems, and the maintenance costs associated with fuel handling and combustion are significantly larger than those associated exclusively with the prime mover.

For these two systems, fixed and variable costs are estimated to be $24.6/kW-yr and 0.3¢/kWh, respectively. For the GSTIG, the fixed costs are comparable to those for the other systems ($24.6/kWW-yr), but the variable costs are lower (0.1¢ /kWh), which can be attributed in part to the absence of heat exchanger

Table 5
Results of financial calculations[a]

Elec Sales Price (/kWh)[b]	5.05.8¢			
Cogen Technology	CEST	GSTIG	CEST	GSTIG
Exported Electricty				
(million kWh/yr)	178	360	178	360
Internal Rates of Return (5/yr)				
Base Case:[c]	13	18	16	23
Alternative GSTIG fuel processing:[d]				
None		24		29
Drying		22		27
Baling/Drying		21		26
Pelletizing		11		16
Alternative Off-Season Fuels:				
Fuelwood chips[e]	12	18	15	24
Oil/biomass[f]	10	11	12	13

[a] For a 206 day season and 90% availability.
[b] Avoided cost based on a new 61-MW coal-fired central-station plant in Jamaica.
[c] During the season, the CEST burns unprocessed, 50% mc bagasse ($1.16/GJ). In the off-season, barbojo (baled, dried) costs $0.97/GJ for the CEST and (briquetted) costs $1.35 for the GSTIG.
[d] Fuel costs ($/GJ) on/off season are: with no processing, 0/0.97; drying, 0.58/0.97; baling and drying, 0.78/0.97; pelletizing, 2.02/2.21.
[e] Wood chips are assumed to cost $1.25/GJ.
[f] The CEST and GSTIG systems would burn residual fuel oil ($2.9/GJ) and distillate fuel oil ($5.4/GJ), respectively, for the first 5 years while barbojo recovery systems are developed, followed by a switch to barbojo (base case conditions).

tubes operating in direct contact with burning solid fuel and in part to higher efficiency.

These maintenance costs, combined with labor cost estimates in the economic assessment described below, result in total O&M cost estimates of 0.77 /kWh for a 27-MW CEST and 0.57¢ / kWh for a 53-MW GSTIG. For the smallest systems described in Table 2, the O&M costs are estimated to be 1.22 ¢/ kWh and 0.76 ¢/kWh for the CEST and GSTIG units, respectively.

Long-Term Outlook

Directly-fired systems would be inherently more efficient than other options because the intermediate step of gasification or indirect heating would be eliminated. The particulate clean-up problem is more formidable than with the GSTIG, however, because of larger gas volumes and higher gas temperatures. Furthermore, to achieve viable system efficiencies, much higher turbine inlet temperatures than those achieved to date will probably be required.

Moreover, to exploit state-of-the-art turbine inlet temperatures will require the development of pressurized slagging combustors to accommodate higher combustion temperatures. Thus, determination of the long-term commercial viability of directly-fired STIGs appears to be several years away.

IFSTIG cogeneration may prove economically interesting in selected applications. However, its competitiveness is limited by electrical efficiencies (Table 2) and unit costs (Fig. 2) that are only modestly more attractive than those for commercially established steam turbine cogeneration systems. IFSTIG performance is limited by the heat exchanger temperature constraint, which is much lower than typical turbine inlet temperatures of state-of-the-art commercial gas turbines.

The biomass-GSTIG appears to be technically and economically the most promising of the three biomass-STIG systems discussed above, with good prospects for further improvements. GSTIG systems will be able to exploit higher turbine inlet temperatures resulting from further developments in aircraft engine technology, which are likely given the very strong military R&D funding base. Performance and economics may also improve is gasifiers optimized for biomass are utilized. For proper operation, the gasifier considered above, the fixed-bed Lurgi Mark-IV, would probably require a relatively dense feedstock similar to the coal chunks for which it was originally designed. For many biomass feedstocks, e.g., sawdust, drop residues and refuse-driven fuel, densification is probably necessary. The expense of densification could be avoided if the gasifier were designed to accommodate the raw biomass feedstocks.

Economics of Biomass GSTIGs

Because of the GSTIG's higher estimated efficiencies and lower capital costs compared to IFSTIGs and CESTs, as well as their promising long-term potential, they have been chosen for detailed economic assessment.

There are large potential near-term markets for biomass-fired gas turbines in the forest products, food processing, and urban refuse processing industries. The economics of GSTIG cogeneration is illustrated in a case study for a hypothetical cane sugar factory modeled after Jamaica's second largest sugar factory, Monymust.

A significant database on the operation of Monymusk was available from a previous study and was augmented by discussions with the chief factory engineer.

Background

Many sugar producers are seeking additional products from sugar cane as part of diversification strategies. One strategy involves using bagasse more efficiently for energy. Bagasse is traditionally used in small steam-turbine cogeneration systems to supply on-site steam and electricity needs, typically 20 kWh of electricity and 400-500 kg of low-pressure steam per tonne of cane processed. Sugar producers in many countries are considering installation of larger, more efficient cogeneration systems to produce excess electricity for sale to the electric utility. Most interest has focussed on condensing-extraction steam turbines (CEST), a simplified performance eestimate of which is shown in Fig. 5. Several such systems are already operating in sugar mills worldwide.

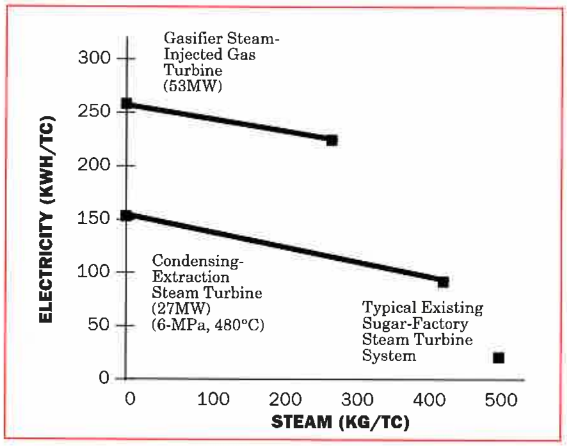

Figure 5. *Ectricity and steam production estimates for alternative bagasse-fired cogeneration systems operating in a sugar factory.*

The GSTIG sysems would produce substantially more electricity, but steam production would be limited to about 300 kg/tc (Fig. 5).A detailed end-use assessment of the Monymusk factory indicates that steam demand could be economically reduced from 400 kg/tc to about 250 kg/tc by retrofitting more efficient technologies currently used in industries more dependent on fossil energy, e.g., beet sugar, diary, and pulp and paper. Such large reductions in steam use are possible, because sugar factories have traditionally been designed to be inefficient so as to consume all the bagasse they produce and avoid disposal costs.

To receive a capacity credit in the price for the electricity they would sell, sugar producers would be required to supply power year-round. Thus, many producers are also considering recovering some barbojo, the tops and leaves of the cane, to store for use as fuel during the non-milling season.

It has been estimated that on a weight basis, about twice as much barbojo as bagasse is produced per ton of cane. Barbojo is typically burned or left on the fields today. Annual electricity exports would rise substantially if barbojo, or an alternative fuel, were used in the off-season (Fig. 6). In the best CEST case, some 240 kWh/tc would be generated, 220 kWh/tc of which would be exported. The GSTIG would produce over 460 kWh/tc, or more than 20 times current production.

Results for Jamaica

The internal rate of return and cost of power generation were calculated for new GSTIG and CEST cogeneration facilities at a hypothetical Jamaican sugar factory processing 175 tons of cane per hour. The bagasse available at the factory would support a 27-MW CEST or a 53-MW GSTIG. Capital, maintenance and operating cost estimates for these systems are summarized in Table 4. (Estimated costs for units that might be installed at smaller factories are also given there.)

The factory steam demand is assumed to be about 250 kg/tc, which would be achieved with an additional $3.1 million of investments in end-use equipment. This additional capital–$115/kW for the CEST, $58/kW for the GSTIG – represents a small increment to the cost of the cogeneration plant (Tablė 4). Three off-season fuel supply scenarios are considered: barbajo, for the base case; fuelwood, should barbojo recovery prove infeasible; and, oil for a 5-year period before switching to a biofuel.

Internal Rate of Return. The rate of return (ROR) depends strongly on the price paid by the utility for the electricity it buys from the sugar producer. Here we assume that, as in the United States under the Public Utility Regulatory Policies Act, this price is equal to the cost the utility can avoid by not otherwise having to provide this electricity. The estimated avoided cost in Jamaica is 5.0-5.8¢/kWh, based on the cost of power from a new 61-MW steam-electric plant burning imported coal.

An investment in a GSTIG system and the steam-conserving retrofits would provide an estimated ROR of 18-23%, compared to 13-16% for a CEST, and exports of electricity would be about double that for the CEST (Table 5). In the base case, assumed fuel costs are higher for the GSTIG (Table 5, Note c), since briquetting is assumed to be necessary to use biomass in the Lurgi fixed-bed gasifier. If less extensive processing than briquetting of bagasse and barbojo were required for the GSTIG, the ROR would increase substantially, while if pelletizing were required, it would fall to near the base-case values for the CEST investment (Table 5).

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, since the off-season fuel costs would be comparable. For the scenarios in which oil is burned during the first 5 off-seasons, the ROR for the CEST and GSTIG are comparable, since the GSTIG would burn distillate fuel oil, while the CEST would burn less costly residual fuel oil. In a fourth scenario, the cogeneration system could be undersized relative to the in-season fuel supply, and excess bagasse stored for use during the off-season (after processing to permit long-term storage), thus avoiding the use of an auxiliary biofuel as well as oil. In this scenario, about half as much electricity would be produced annually, and the RORs 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).

Levelized Cost of Electricity Generation. While the GSTIG would provide much more attractive rates of return to a sugar producer than would a CEST plant, the capital involved in either case would be very large for a sugar producer. Furthermore, the electricity revenues (at 5¢/kWh) would be about double the sugar revenues (at the 1986 world-market sugar price), so that the sugar factory would begin to resemble a utility power-plant producing sugar as a by-product. But from the perspective of an electric utility, the cogeneration investment would typically be less than what it might invest in building a comparable amount of new central station capacity.

Cogenerated electricity would be of interest to the utility if it cost less than other utility sources. With utility financing and the base-case conditions of Table 5 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. These cogeneration costs, and those for smaller installations, are compared in Fig. 7 to the cost of power from a new 61-MW coal-fired power plant. The 53-MW GSTIG plant would provide substantially lower-cost electricity than the coal-fired option, even with a low coal price. The cost of exported electricity is also compared to the operating cost of existing Jamaican oil-fired plants, which supply over 90% of the ocuntry's electricity. For all cases where biomass is the sole fuel, the GSTIG facility would

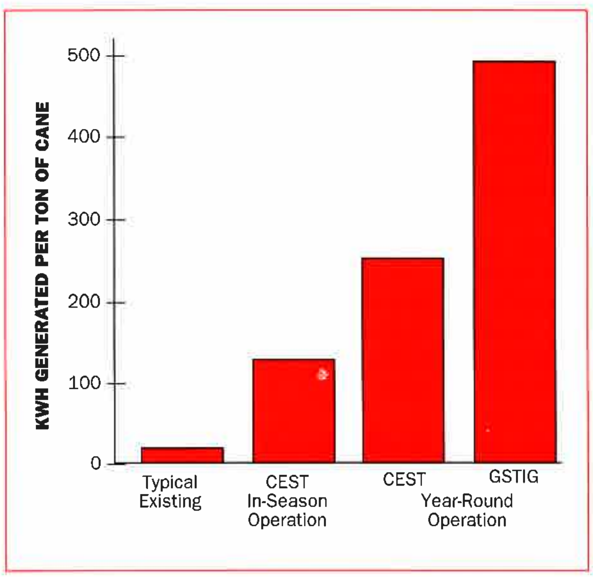

Figure 6. *Potential cogeneration of electricity using sugar cane residues. Left bar shows typical existing situation at a sugar factory during the milling season. Next bar shows CEST system operating during the milling season at a factory where steam-saving retrofits have been made. Third bar shows CEST at the steam-saving factory operating year-round. Right bar shows GSTIG at the steam-saving factory operating year-round.*

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.

Results for Southeast Brazil

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, the installation of new hydro capacity is under consideration. Since most 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. Electricity from such facilities, including transmission, is estimated to cast from 3.2 to 5.8¢/kWh (Fig. 7).

Based on the calculations for Jamaica, 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 costs 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).

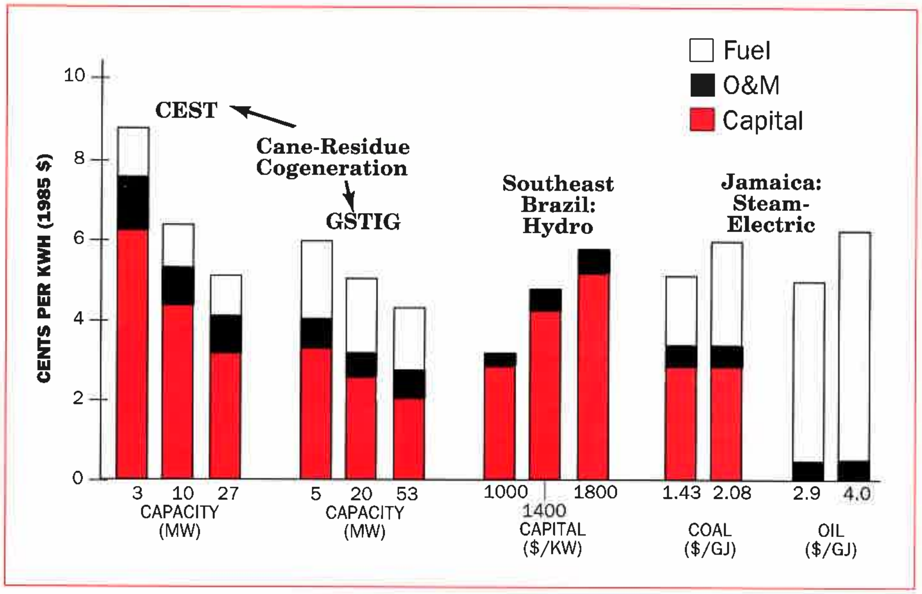

Figure 7. *Estimated levelized costs of generating exportable electricity at cane-residue-fired cogeneration plants and at least-cost central station power plants in Jamaica and Southeast Brazil.*

Global Markets for Biomass-GSTIGs

Based on the assessment presented above, biomass-GSTIG cogeneration systems at sugar factories would provide significant technical and economic benefits compared to commercially-established CEST systems. The introduction of GSTIG units worldwide could have a significant impact in over 70 countires that grow cane. The 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. Based on an extrapolation of the results for Jamaica, some 300 TWh of electricity could be produced at the 1985 level of cane production in all developing countries. This is about 1/4 of the electricity generated by utilities in these countries today and is comparable to the level of electricity generated with oil.

For candidate GSTIG manufacturers, potential cane-sugar markets appear large enough to justify the devlopment 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-1990s—would insure secure markets in the future. The potential cane-sugar GSTIG market may be still larger is 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. Although the fuel-alcohol industry is developed on a large scale today only in Brazil, this situation may change, if, as expected, oil prices rise considerably in the next 10-15 years.

There are also large potential global markets for gas turbines using other biomass processing residues, and in the longer term, dedicated energy plantations might provide fuel for stand-alone GSTIG power plants. For developing countries, such energy complexes would be located in rural areas, where they could help alleviate problems of unemployment and urban drift both directly and by supplying electricity at reasonable cost to help spur agricultural development and rural industrialization.

Research, Development, and Demonstration Needs

Commercializing biomass-GSTIGs will require a successful demonstration of the integrated operation of technically proven components. A first step would be to undertake pilot-scale testing of various biomass feedstocks to assess the pre-processing requirements for pressureized fixed-bed gasification. Most of the other key enginering issues, including hot-gas particulate clean-up and low-btu gas combustion, have already been addressed in coal-GSTIG work, as discussed earlier.

Thus, it appears that a demonstration project could be undertaken in the near term. The required R&D investment should be modest, because it would piggyback on the previous coal-related work. Furthermore, a small (5-20 MW) demonstration would be sufficient to prove the technology, since this represents a commercial size for many biomass applications.

For the longer term, the economic assessment presented here suggests that R&D efforts should be directed toward identifying gasification systems that are optimized for biomass, with particular attention paid to minimizing pre-processing of the feedstock.