May 29, 1990

COGENERATION APPLICATIONS OF BIOMASS GASIFIER/GAS TURBINE TECHNOLOGIES IN THE CANE SUGAR AND ALCOHOL INDUSTRIES

Getting Started with Bioenergy Strategies for Reducing Greenhouse Gas Emissions

by

Joan M. Ogden, Robert H. Williams, and Mark E. Fulmer
Center for Energy and Environmental Studies
Princeton University
Princeton, NJ 08540

prepared for the session

on

Industrial Processes and Materials Manufacture: an Overview
March 27, 8:30-12:00 noon

of the

Conference on Energy and Environment in the 21st Century
Massachusetts Institute of Technology
Cambridge, MA 02139
March 26-28, 1990

TABLE OF CONTENTS

	Page
INTRODUCTION	1
SUITABILITY OF SUGAR CANE INDUSTRIES FOR INITIAL APPLICATIONS OF BIG/GTs	2
ALTERNATIVE TECHNOLOGIES FOR COGENERATION IN THE CANE INDUSTRIES	4
INTEGRATING COGENERATION SYSTEMS WITH SUGAR FACTORIES OR ALCOHOL DISTILLERIES	6
PROCESS TECHNOLOGIES FOR AUTONOMOUS DISTILLERIES	8
DESIGN OF AUTONOMOUS DISTILLERIES FOR COGENERATION APPLICATIONS	10
PROSPECTIVE ECONOMICS FOR THE COPRODUCTION OF ALCOHOL AND ELECTRICITY	11
GLOBAL POTENTIAL FOR CANE ENERGY AND GREENHOUSE GAS EMISSIONS REDUCTION	14
PUBLIC POLICY ISSUES	16
ACKNOWLEDGMENTS	22
REFERENCES	
TABLES	
FIGURES	

ABSTRACT

Biomass integrated gasifier/gas turbine (BIG/GT) technologies for cogeneration or stand-alone power applications hold forth the promise of being able to produce electricity at lower cost in many instances than most alternatives, including large central-station, coal-fired, steam-electric power plants with flue gas desulfurization, nuclear power plants, and hydroelectric power plants. BIG/GT technologies offer environmental benefits as well, including the potential for zero net carbon dioxide emissions, if the biomass feedstock is grown renewably.

The gas turbine, in various power cycle configurations, is emerging as the technology of choice for thermal power generation, since the low unit capital cost of the gas turbine can now be complemented by high thermodynamic efficiency, owing largely to substantial technological improvements that have been made as a result of support for jet engine R&D for military aircraft applications.

The marriage of coal to the gas turbine through the use of coal-integrated gasifier/gas turbine (CIG/GT) technologies has been demonstrated. Some CIG/GT technologies could be be readily transferred to biomass with modest incremental R&D effort. In fact, biomass is inherently easier to gasify than coal. Moreover, BIG/GT technologies could probably be commercialized more quickly than corresponding CIG/GT versions, because most biomass contains negligible quantities of sulfur, the efficient and cost-effective removal of which is the major technological hurdle that must be overcome before cost-competitive CIG/GT technologies can be commercialized.

Particularly promising for biomass applications is the combination of an airblown biomass gasifier (fixed bed or fluidized bed) with various gas turbine technologies directly derived from aircraft engines (aeroderivative turbines). Using airblown gasifiers with aeroderivative turbines makes it possible to achieve both high efficiency and low unit capital costs at the modest scales needed for biomass applications.

Eventually biomass grown on plantations dedicated to energy production could be the fuel for BIG/GT systems that generate power only. However, initial applications of these technologies will likely be for the cogeneration of electricity and process heat in industrial and agricultural industries where biomass residues are readily available as fuel.

For developing countries, the sugar cane industries that produce sugar and fuel alcohol are promising targets for near-term applications of BIG/GT technologies. In these industries, bagasse (the residue left after crushing the cane) could be used as BIG/GT fuel to provide the steam and electricity needs of the sugar factory or alcohol distillery during the milling season and to generate excess electricity for "export" to the utility grid. The barbojo (the tops and leaves of the sugar cane plant) could also be harvested and stored for use as fuel to produce more electricity during the offseason.

Depending on the choice of gas turbine technology and the extent to which barbojo can be used this way, the amount of electricity that can be produced

from cane residues could be up to 44 times the onsite needs of the sugar factory or alcohol distillery. Revenues from the sale of electricity coproduced with sugar could be comparable to sugar revenues, while revenues from the sale of electricity coproduced with alcohol could be much greater than alcohol revenues. In the latter instance, electricity would become the primary product of cane, and alcohol the byproduct. Electricity coproduction could help improve the economics of sugar and alcohol production. Under Brazilian conditions coproduction could make fuel alcohol highly competitive, even at the present depressed world oil price.

If sugar cane production were to continue to grow at the historical rate of 3 percent per year, and if BIG/GT technologies were fully deployed in the cane industries in forty years time, then at the end of this period, potential electricity production from cane in the 80 sugar cane-producing developing countries would be up to 2800 TWh/yr, about 70% more than total electricity production in these countries from all sources in 1987. Assuming 45% of all cane at that time would be associated with producing alcohol, cane alcohol production at the end of this period would be equivalent to 3.3 EJ/yr of crude oil, about 9% of total oil use in all developing countries in 1987.

Assuming that "cane electricity" displaces electricity that would otherwise be produced with coal and that the fuel alcohol displaces petroleum, total carbon dioxide emissions in these 80 developing countries after 40 years would be 0.75 gigatonnes of carbon per year less than they would otherwise be. For comparison total carbon dioxide emissions from all fossil fuel use in all developing countries totalled 1.55 gigatonnes of carbon in 1986.

Efficient and cost-competitive BIG/GT technologies suitable for widespread use in the cane sugar industries could be commercialized in less than five years time at modest cost. Commercialization of these technologies would serve many development objectives while simultaneously helping cope with the problem of global warming.

INTRODUCTION

The use of biomass as an energy source is one promising strategy for coping with the greenhouse problem. The combustion of biomass grown renewably leads to no net buildup of carbon dioxide in the atmosphere.[1] Moreover, if the biomass feedstock is grown in "energy plantations" with multi-year growing cycles on deforested or previously unforested land, the carbon extracted from the atmosphere in photosynthesis and sequestered in the steady state inventory of such plantations can be significant.

The US Environmental Protection Agency recognized the importance of bioenergy in its exploration of global energy strategies for reducing CO_2 emissions (2). The EPA projected that while under business-as-usual conditions global CO_2 emissions would double by 2025 and triple by 2050, emissions could be roughly stabilized by pursuing appropriate energy demand and supply side strategies--with bioenergy strategies accounting for roughly 3/5 of the projected potential reduction in CO_2 emissions (Table 1).

Biomass is already a significant global energy source--accounting for an estimated 48 EJ/yr in developing countries and 7 EJ/yr in industrialized countries at present (3)--in developing countries roughly equivalent to oil and coal use combined (Table 2). Despite its magnitude, bioenergy does not usually show up in the energy production and use statistics of developing countries, because most of it is used there as noncommercial energy--fuelwood, crop residues, and dung. Moreover, it is typically used inefficiently, mostly in crude cooking stoves. To play a major role as an energy source, bioenergy must be elevated from its present status as the "poor man's oil" into a modern energy source, by using advanced techniques to produce it renewably and to convert it efficiently into electricity and gaseous, liquid, and processed solid fuels (4).

Among the advanced technologies for modernizing bioenergy that could be commercialized in the near term, biomass integrated gasifier/gas turbine (BIG/GT) power generating technologies stand out as especially promising. The gas turbine, in various power cycle configurations, is emerging as the technology of choice for thermal power generation in the decades ahead, since the low unit capital cost of the gas turbine can now be complemented by high thermodynamic efficiency, owing largely to substantial technological improvements that have been made as a result of Defense Department support for jet engine R&D for military aircraft applications (5). The marriage of coal to the gas turbine through the use of coal-integrated gasifier/gas turbine (CIG/GT) technology has been demonstrated at Cool Water, California (6). While the particular technology demonstrated there is not likely to be adopted by utilities, because the commercial version would be no less costly than coal

---

[1] If fossil fuels are required to produce biomass and convert it into useful energy carriers, then this is not strictly true. For some high-cost biofuels (e.g. ethanol produced from corn), net energy gains in biofuel production can be small (1), so that net CO_2 reductions achievable with a shift to such biofuels would be small (and might even be negative). However, as will be shown, these fossil fuel energy penalties are small for the sugar cane applications considered here.

steam-electric power generating technology (5), there are various possibilities for reducing the unit capital cost and improving efficiency (7).

Some CIG/GT technologies could be be readily transferred to biomass with modest incremental R&D effort. In fact, biomass is inherently easier to gasify than coal. Moreover, BIG/GT technologies could probably be commercialized more quickly than corresponding CIG/GT versions, because most biomass contains negligible quantities of sulfur, the efficient and cost-effective removal of which is the major technological hurdle that must be overcome before cost-competitive CIG/GT technologies can be commercialized (8).

Particularly promising for biomass applications is the combination of an airblown biomass gasifier (fixed bed or fluidized bed) with various aeroderivative turbine technologies (8). Gasification in air, instead of oxygen (used with Cool Water technology) makes it possible to eliminate the oxygen plant, the capital cost of which is very scale-sensitive. Using airblown gasifiers with aeroderivative turbine technologies such as the steam-injected gas turbine (STIG--Figure 1a) or the intercooled steam-injected gas turbine (ISTIG--Figure 1b) instead of the gas turbine-steam turbine combined cycle (GT/ST CC--Figure 1c) used at Cool Water makes it possible to achieve both high efficiency and low unit capital costs at the modest scales needed for biomass applications. Because of the dispersed nature of the biomass resource (arising from the low efficiency of photosynthesis), biomass power plants must be relatively small in scale (less than 100 MW) to avoid high fuel transport costs. At these scales the unit capital cost of the GT/ST CC is relatively high, because of the strong scale economy associated with the steam turbine bottoming cycle. But the scale sensitivity of STIG and ISTIG cycles is much more modest, because these cycles do not require steam turbine bottoming cycles to achieve high efficiency (5).

Eventually biomass grown on plantations dedicated to energy production could be the fuel for BIG/STIG or BIG/ISTIG systems that generate power only (9). However, initial applications of these technologies will likely be for the cogeneration of electricity and process heat in industrial and agricultural industries where biomass residues are readily available as fuel.

SUITABILITY OF SUGAR CANE INDUSTRIES FOR INITIAL APPLICATIONS OF BIG/GTs

Sugar cane is a well-established, photosynthetically-efficient crop. Global sugar cane production has been growing since the early 1960s at an average rate of about 3%/yr and now totals nearly a billion tonnes per year (Table 3). The global average cane productivity is about 58 tonnes/ha/yr (10)[2]--equivalent as an energy feedstock to woody biomass production at a rate of 38 dry

---

[2] The mass at harvest of the sugar cane stalks, which does not include the mass of the barbojo (the word for the tops and leaves of the sugar cane plant used in Latin American countries). The barbojo is typically burned off just before harvest, to facilitate harvesting the cane stalks.

tonnes/ha/yr.[3] For comparison, yields of only about 10 dry tonnes per hectare per year have been achieved to date in US short rotation intensive culture demonstrations (13). While yields as high as 40 dry tonnes/ha/yr have been achieved for some plantations in developing countries, such yields have not yet been achieved on a large scale. While some day such productivities might be routinely achievable for wood plantations, it is already known how to achieve such high yields with sugar cane. Thus sugar cane seems to be a good initial target for efforts to begin a transition to an energy economy in which biomass plays a major role.

One economic motivation for cogenerating electricity as a byproduct of sugar production is to help stabilize revenue flows over time to sugar producers. Sugar is a commodity whose world market price has fluctuated widely (Figure 2). In contrast, it should be feasible, in principle, to sell electricity cogenerated at sugar factories to electric utilities for stable prices under long-term contracts. Sales of cogenerated electricity by sugar producers could be an important economic stabilizing activity, since the revenues from power sales would often be comparable to the revenues from sugar sales.

The prospect of shrinking markets for sugar is also stimulating interest in alternative products from cane, such as electricity. The demand for sugar is expected to continue growing in developing countries, owing to population growth and rising living standards, but future growth in the demand for sugar is expected to be much slower than in the past, largely because of the growing importance (in hard currency markets) of grain-based sweeteners, particularly high fructose corn syrups (HFCS). As a result the World Bank has projected that world demand for sugar will increase at an average rate of only 1.5%/yr through 1995 (14). Moreover, two potential developments may further erode sugar demand growth in the period near the turn of the century and beyond: the introduction of crystallized HFCS and the progressive introduction of new low-calorie sweeteners with physical and taste properties closer to those of sugar (14).

---

3 Alcohol can be produced from sugar cane with a yield of about 70 liters per tonne of cane (tc) or 1.68 GJ/tc.[4] If instead this much alcohol were produced from wood some 3.36 GJ of woody feedstock would be required, assuming a 50% conversion efficiency (11). In addition, methane can be recovered with a yield of about 0.33 GJ/tc from the stillage at cane distilleries via anaerobic digestion (12). To recover this much methane via wood gasification would require 0.49 GJ of woody feedstock, assuming a gasification efficiency of 67%. In addition, the bagasse residue left after extracting the sugar juice from cane amounts to 300 kg/tc (50% moisture) or 2.85 GJ/tc, and the barbojo is another potentially usable residue amounting to some 660 kg/tc (50% moisture) or 6.27 GJ/tc. Thus the total woody biomass equivalent of 1 tonne of harvested cane is

$$3.36 + 0.49 + 2.85 + 6.27 = 12.97 \text{ GJ or } 0.65 \text{ tonnes dry weight,}$$

for wood @ 20 GJ/tonne.

4 In this paper higher heating values are used for fuels.

One alternative is ethanol produced from the fermentation of sugar juice. The technologies for producing fuel ethanol from sugar cane and using it as an automotive fuel have been developed on a large scale in Brazil (15-17). Alcohol production there increased from 3.4 billion l/yr in 1979/80 to 11.5 billion l/yr in 1987/88, accounting for 4.5% of all energy consumed in Brazil then. Several other developing countries are producing fuel ethanol from cane molasses (14,18-27) (Table 4), and in some of these countries national alcohol fuel programs have been implemented or are being considered (14-19).

Unlike the situation for ethanol derived from corn in the US, for which net energy balances can be unfavorable (1), energy balances for producing ethanol from cane are highly favorable. For Brazil, the agricultural energy required to produce a tonne of cane amounts to 305 MJ/tc, while the energy required to manufacture, operate and maintain the distilleries requires another 143 MJ/tc (excluding the bagasse used as distillery fuel) (28,29). As each liter of hydrous alcohol is equivalent as a "neat" (unblended) automotive fuel to 0.84 liters of gasoline (11), the 70 liters of alcohol that can be produced from a tonne of cane is equivalent to 4.2 times as much gasoline energy as the energy required to produce the ethanol. For Louisiana, where cane yields are comparable to those in Brazil but cane production is much more mechanized, the energy output/input ratio is lower, 2.9:1 (30,31), but still very favorable. For Hawaii, where cane production is also heavily mechanized but annual cane yields are twice as high as in Brazil or Louisiana, the energy output/input ratio is comparable to that for Brazil (31). The useful energy output/input ratios for cane would be substantially improved improved if electricity were produced as a byproduct of alcohol, since the energy content of cane residues (bagasse and barbojo) is over five times the energy content of the alcohol.

Despite the impressive advances that have been made in the productivity of alcohol production in Brazil,[5] cane-derived ethanol is not competitive as a neat fuel at today's low world oil price, although it is approximately competitive as a gasoline extender (gasohol).[6] As we shall show, the coproduction of

---

5 Between 1979/80 and 1987/88 the cost of producing alcohol in Brazil declined 4% per year, on average. Also, the average productivity of cane fields increased from 2663 l/ha/yr in 1977/78 to 3811 l/ha/yr in 1985/86 (32).

6 The present production cost of ethanol in Brazil is 21 cents per liter. One liter of ethanol is worth 0.84 liters of gasoline as a neat fuel (11) and 1.16 liters of gasoline as "gasohol," an octane-enhancing additive to gasoline (33). At the present world oil price ($20/barrel), the wholesale gasoline price is 17.7 cents/liter,[7] so that the present value of ethanol is 14.9 cents/liter as a neat fuel and 20.5 cents/liter as gasohol.

7 The wholesale gasoline price Pgas (in cents per liter) can be expressed in terms of Pcrude, the refiner acquisition cost of imported crude oil in the US (taken to be the world oil price), in dollars per barrel, as:

$$Pgas = 6.26 + 0.572*Pcrude, \quad r = 0.99067,$$

obtained by regression of data for the period 1980-1989.

alcohol and electricity using BIG/GTs could make ethanol competitive as a neat fuel in Brazil, even at today's low world oil price.

Thus sugar cane industries producing sugar or alcohol are good initial candidates for initial applications of BIG/GT technologies.

ALTERNATIVE TECHNOLOGIES FOR COGENERATION IN THE CANE INDUSTRIES

In most sugar factories and alcohol distilleries today, small, bagasse-fired steam turbine systems supplied with steam at 1.5-2.5 MPa provide just enough steam and electricity to meet onsite factory needs, typically about 350-500 kilograms of steam, and 15-25 kWh of electricity per tonne of cane milled (34,35). Typically, factories are designed to be somewhat energy inefficient, consuming all the available bagasse while just meeting factory energy demands, so that excess bagasse does not accumulate and become a disposal problem. [In Southeastern Brazil, where bagasse is sold as a boiler fuel or as a component of cattle feed (36,37), some factories have been made more energy efficient so as to free up surplus bagasse for these markets (38-41).]

In a few sugar factories and alcohol distilleries, modern condensing-extraction steam turbine cogeneration systems (CEST) operated at turbine inlet pressures of 4.0-8.0 MPa have been installed (42,43,38). With these systems, it is possible to produce enough steam to run a typical factory 350-500 kg/tc, plus 70-120 kWh/tc of electricity, or about 50-100 kWh/tc in excess onsite needs. The extra electricity can be made available to other users by interconnecting the cogenerator with the utility grid. During the milling season the CEST cogeneration system is fueled with 50% wet bagasse, as it comes from the mill. In the off-season, CEST units can be operated in the condensing mode producing power only, fired with barbojo (cane tops and leaves), wood or heavy fuel oil.

While the introduction of modern CEST units can improve the performance of sugar or alcohol factories, Rankine cycles are relatively inefficient for the steam conditions that can be used at the modest scales needed for biomass applications,[8] and the strong scale sensitivity of the capital cost (Figure 3) makes CEST technology only marginally attractive for many applications.

Much better thermodynamic and economic performance could be achieved at the modest scales needed for biomass-fired applications if BIG/GT systems could be used instead. The first generation BIG/GT technology may well be BIG/STIG (8), combining a commercially available pressurized fixed bed gasifier with a steam-injected gas turbine (Figure 1a), which is commercially available for natural gas applications (5).

In a BIG/STIG cogeneration system, biomass would be gasified in air to form

---

8 A 27 MW steam turbine unit supplied with steam at 6 MPa would have an efficiency of only 20% in producing power only (Table 5). Of course higher efficiencies can be achieved with the steam Rankine cycle at the larger scales of central station power plants, for which it is economical to operate at much higher quality steam conditions. A modern 500 MW central station steam turbine unit with 16.5 MPa steam has an efficiency of about 35%.

a gas of low energy content (having perhaps 15-20% of the heating value of natural gas), which fuels a gas turbine. Steam is raised for the mills, for the gasifier, and for process needs in a heat recovery steam generator (HRSG), which utilizes the hot exhaust gases exiting the turbine. Any steam not needed for the factory or the gasifier could be injected into the combustor or the turbine, boosting the electrical output and efficiency of the system.

As in the case of CEST technology, the BIG/STIG system would be fueled with bagasse during the milling season. However, the bagasse would probably have to be densified (either briquetted or pelletized) if used in a fixed bed gasifier originally designed for use with coal (8). In the off-season the system could be fueled with densified barbojo, wood or distillate oil.

Because of their much higher electrical efficiencies (Table 5) and lower unit capital costs (Table 6 and Figure 3), BIG/STIG systems would be able to provide more than twice as much electricity per tonne of cane at lower costs than CEST systems.

BIG/STIG could be the first of a series of increasingly attractive gas turbine systems that could be designed for biomass applications. Even higher efficiencies, more electricity production per tonne of cane, and lower unit capital costs could be achieved coupling an intercooled steam-injected gas turbine (ISTIG) instead of a STIG unit to the biomass gasifier (Tables 5 and 6). By adding an intercooler to the compressor (Figure 1b), the output of the turbine would more than double and the turbine efficiency would be significantly increased (Table 5). These performance improvements arise because with intercooling less compressor work is required, and it is possible to operate at a significantly higher turbine inlet temperature (TIT). The cooler turbine blade coolant air bled from the compresor makes it possible for the turbine to operate at a higher TIT without violating metallurgical temperature limits on the blades (8). As in the case of the BIG/STIG, the BIG/ISTIG would be fuelled with densified bagasse during the milling season and with densified barbojo, wood, or distillate oil during the off-season.

While BIG/STIG and BIG/ISTIG systems are not commercially available at present, they could probably be commercialized much more quickly than the corresponding coal-fired systems because there would be no need for sulfur removal technology with most biomass feedstocks, including cane residues. Not having to remove sulfur means that the unit capital costs for biomass systems would probably be about 20% less than for the corresponding coal-fired versions of these technologies (Table 7).

It is estimated that BIG/STIG technology could be commercialized less than five years (44). The R&D effort required to commercialize the BIG/STIG system would be relatively modest, because much of the development work already carried out for coal integrated gasifier/steam-injected gas turbines (7) would be applicable to biomass (45). ISTIG technology would probably be commercialized first using natural gas as fuel, which would require a 4-5 year development effort (44). If this technology were developed at the same time as BIG/STIG technology, BIG/ISTIG technology could become commercially available shortly thereafter. More detailed discussions relating to the commercialization of these technologies are presented elsewhere (5,8,45).

INTEGRATING COGENERATION SYSTEMS WITH SUGAR FACTORIES OR ALCOHOL DISTILLERIES

Figure 4 shows schematically how various cogeneration systems could be integrated with a sugar factory or alcohol distillery. Figure 4a shows a typical existing sugar factory steam turbine cogeneration system, producing just enough steam and electricity for factory needs. Steam is produced at "moderate" pressure (1.5-2.0 MPa) for use in back-pressure cane mill and turbo-alternator turbines. The "low pressure" (0.15-0.25 MPa) exhaust steam from these turbines is then used to provide heat for processing the cane juice into sugar or alcohol. In Figure 4b a CEST cogeneration system is shown. Steam is extracted at 1.5-2.0 MPa for use in the factory as before. About 50-100 kWh/tc of electricity in excess of onsite needs can be produced during the milling season. A biomass gasifier/gas turbine cogeneration system is shown in Figure 4c. With the BIG/STIG system about 240 kWh/tc of excess electricity is produced during the milling season. With a BIG/ISTIG system (not shown) excess electricity production would increase to about 285 kWh/tc in season.

In order to use a particular cogeneration system at a sugar factory or alcohol distillery, the system must meet the factory's steam and electricity needs. Figure 5 shows the steam and electricity production for CEST, BIG/STIG and BIG/ISTIG cogeneration systems, operated on biomass fuel. For each technology, a range of operating values is possible, depending on how much steam is produced for process. For each system, the lower the process steam demand, the higher the electricity production. When the process steam demand is zero, as in off-season operation, electricity production is maximized. The maximum steam production possible with the system is given at the right hand endpoint of each line. Also shown are the steam and electricity demands for typical existing sugar factories or alcohol distilleries.

The more electrically efficient gas turbine cogeneration systems have lower steam production than the CEST system. With BIG/STIG steam can be produced at a maximum rate of about 300 kilograms (@ 2.0 MPa, 316 °C) per tonne of cane milled (kg/tc). With BIG/ISTIG maximum steam production is about 230 kg/tc. Since a typical existing sugar factory or alcohol distillery requires about 350-500 kg/tc of process steam, factory steam economy improvement measures must be carried out before gas turbine cogeneration systems can be installed.

It has been shown that by adapting to the cane sugar industry steam economy measures widely used in other process industries, it would be feasible to integrate gas turbine cogeneration technologies into cane sugar factories (46-48). In the present paper this analysis is extended to autonomous alcohol distilleries, in which ethanol is produced directly from sugar juice. A more general treatment, also showing how to integrate gas turbine cogeneration technologies into distilleries annexed to sugar factories that coproduce sugar, alcohol, and electricity, is given elsewhere (49).

When sugar cane is delivered to an autonomous distillery, it is washed, chopped and then milled in a series of roller mills to extract "raw" cane juice, which typically contains over 90% of the sucrose in the cane. The raw cane juice is filtered and heated. In some Brazilian autonomous distilleries, the juice is then cooled and sent directly to the fermentation stage. Alternatively the juice can be limed and clarified, and the clear juice is often concentrated in an evaporator from typical values of 13 ° Brix (13% solids in juice) to about 18-20° Brix, which is preferable for fermentation. The concentrated juice is then fermented to produce a "beer," a water/ethanol mixture which is typically 8-10% ethanol. The beer is distilled to produce about 70 liters of ethanol per tonne of cane milled. In addition, methane can be produced via anaerobic digestion from the stillage (a waste product of distillation), typically at a yield of about 0.33 GJ/tc (12), about 1/5 of the energy content of the alcohol.

Alcohol distilleries would be modest in scale and capital cost compared to fossil synfuel facilities. A "large" distillery would be one processing 4000 tonnes of cane and producing 280,000 liters of ethanol per day--equivalent on an contained energy basis to about 1,200 barrels of gasoline per day. While published estimates of the installed capital cost of autonomous distillery equipment vary widely (14,16,23,24,27,50,51), such a distillery, if built in Brazil, where virtually all distilleries have been built, would cost about $18 million (Table 8). By way of contrast, a plant producing methanol from coal would typically produce methanol at a gasoline energy-equivalent rate of 20,000 barrels per day and cost $1.5 billion (52).

The process steam, mechanical work, and electricity requirements of the distillery are provided by using bagasse as fuel. Steam and electricity use in a typical Brazilian autonomous distillery producing hydrous ethanol are shown in Table 9 (first column) and Figure 6a (38). A conventional distillation system requiring 3.3 kilograms of low pressure (0.15-0.25 MPa) steam per liter (kg/l) of hydrous ethanol is used. The overall factory steam demand for this case is 5.8 kg/l, or 466 kg/tc. [A recent survey of autonomous distilleries in the Sao Paulo area indicated steam use of 420-550 kg/tc (41).]

PROCESS TECHNOLOGIES FOR AUTONOMOUS DISTILLERIES

There are many possible design options for the coproduction of alcohol and electricity from cane (Table 10). For each cogeneration option, a set of end-use technologies is needed that will make it possible to serve the steam needs of the distillery with the heat output of the cogeneration system, while making as much electricity as can be justified cost-effectively. As already noted, this implies that steam economy measures must be implemented before gas turbine cogeneration systems can be employed.

The main uses of moderate pressure steam in a conventional autonomous distillery (first column, Table 9) are for running turbines to provide the mechanical power needed for cane milling (226 kg/tc) and for generating electricity (175 kg/tc). The low pressure exhaust steam from these turbines (plus some 65 kg/tc of steam which is throttled to low pressure) is then used for distillation (256 kg/tc), evaporation (61 kg/tc) and juice heating (130 kg/tc). Here the various technologies which could be used for each stage of the process are described, noting opportunities for steam conservation. Details are presented elsewhere (49).

<u>Cane Preparation/Milling</u>: To extract the sugar juice, the cane is typically chopped, shredded, and crushed in a series of roller mills. In virtually all autonomous distilleries and sugar factories, the mechanical power requirements

for these cane preparation and milling operations are provided by back-pressure steam turbines. Typically, these turbines require 200-250 kg steam/tc at 1.5-2.0 MPa and exhaust steam at 0.15-0.25 MPa. These operations could also be driven by electric motors. Alternatively, a diffuser could be used to extract the sugar from the cane. In a diffuser the cane is chopped, shredded and immersed in water to extract the sugar, and the fibers are then dewatered in a single set of roller mills.

The low-pressure (0.15-0.25 MPa) exhaust steam from mill turbines is utilized for process heat (juice heating, evaporation, distillation). Unless the demand for low-pressure steam is less than the amount of this exhaust (e.g. less than about 200 kg/tc), there is little reason to reduce the steam use in cane preparation and milling. However, if the demand for low- pressure steam were reduced, it would be feasible to reduce steam consumption in these operations by using more efficient, higher pressure turbines or by using diffusers or electric mills.

Juice Heating: In autonomous distilleries, juice is generally heated directly with exhaust steam or with vapor bled from the evaporator. Depending on the configuration, bleeding vapor from the evaporator can reduce steam use. In some cases the hot condensates from the evaporator can be utilized, saving some steam.

Evaporation: Evaporation is typically done in multi-effect, short-tube, rising-film evaporators. Increasing the number of effects can reduce the steam needed for evaporation. If rising-film evaporators are replaced with falling-film evaporators, which can operate at higher temperatures and thus make better use of multiple-effect evaporator configurations, overall steam use can be reduced. Falling film evaporators are widely used in the beet sugar, dairy, and some other process industries and are being used experimentally in the cane sugar industry (21,46).

Distillation: After fermentation, the ethanol must be separated from the other components of the "beer". (Beer is about 8-10% ethanol. Most of the rest is water, with traces of fusel oils and other impurities.) Distillation is by far the most common ethanol separation process, although a number of other techniques have been developed (53-55). (See Table 11 for a summary of ethanol separation technologies.) The purity of the alcohol produced is determines the type of distillation equipment required. Hydrous alcohol (96%-96.5%) is used for unblended motor fuel; absolute or anhydrous alcohol (99.9%), is often used for blending with gasoline. The purer the final ethanol, the more complex the distillation process. In this paper emphasis is given to the production of hydrous ethanol for use as a neat motor fuel.

Over half the steam use in a typical autonomous distillery goes to distillation (Table 9). Until recently, relatively little attention was given to energy efficiency in cane alcohol distilleries. However, with the large-scale development of a cane-based fuel alcohol industry in Brazil and competitive pressures on this industry as a result of the low world oil price, there is growing interest in more efficient distillation technology. Brazilian manufacturers have developed energy-saving conserving distillation systems for use in autonomous distilleries. With these commercially available Brazilian systems the demand for steam has been reduced from 3.0-3.5 kg/liter of hydrous ethanol to 1.5-2.0 kg/liter (15,16,36).

One way to reduce steam requirements for distillation is through the use of heat integration techniques that use hot and cold streams within the factory as efficiently as possible to accomplish the required heating with a minimum of external steam input (53,56). With optimized heat integrated ethanol distillation systems, it is feasible to reduce distillation steam use to 1.2 kg/liter for motor grade hydrous ethanol and to 2.2 kg/liter for anhydrous ethanol (56) or less (53) (Table 11). Through the use of mechanical vapor recompression systems, which substitute electricity for steam, overall heat requirements for distillation could be reduced further. These systems have been used for ethanol production but not in the cane sugar industry (53,56).

Dramatic energy savings are theoretically possible if non-distillation separation techniques are used (53,54). Several of these methods have been demonstrated at the laboratory scale (Table 11), but none are in commercial use.

DESIGN OF AUTONOMOUS DISTILLERIES FOR COGENERATION APPLICATIONS

The alternative distillery designs that can be considered for the coproduction of alcohol and electricity with CEST, BIG/STIG or BIG/ISTIG cogeneration systems include both conventional and steam-conserving options.

Conventional Distillery Designs: Figure 6a shows a factory flow diagram for a conventional Brazilian autonomous distillery, which mills 125 tonnes of cane per hour to produce 10,000 liters of hydrous ethanol per hour (80 liters of ethanol per tonne of cane) (38). The juice is heated, clarified, concentrated in a conventional short-tube, rising-film, 3-effect evaporator, fermented, and distilled in a conventional two-column distillation system requiring 3.2 kg steam per liter of hydrous ethanol produced. The overall steam demand for the factory is 5.8 kg/liter of alcohol or 466 kg/tc--comparable to the amount of steam required in a typical sugar factory (34,35). A CEST cogeneration system could meet the process steam demand for this type of factory, producing 90-95 kWh/tc of excess electricity during the milling season (Table 9, first column).

Steam-Conserving Distillery Designs: The largest single use of steam in the conventional factory is for distillation, about 3.2 kg steam per liter of hydrous ethanol or 256 kg/tc--see Table 9. The next largest use of steam in the factory is for juice processing (juice heating and evaporation to 18° Brix), some 130 kg/tc. There are various opportunities for steam conservation in autonomous distilleries.

Consider first a design requiring 1.9 liters of steam per liter of hydrous alcohol (155 kg/tc) for distillation--consistent with designs demonstrated in Brazil for which steam used for distillation is reduced from 3.0-3.5 kg/liter to about 1.5-2.0 kg/liter by using a higher pressure distillation system with heat integration (16). The total amount of steam used for juice heating plus evaporation can be reduced by using a five-effect evaporator and by bleeding vapor from the evaporator for juice heating. The factory flows for this steam-conserving factory with a low steam use distillery and an energy efficient juice processing system are shown in Figure 6b (38). The total steam demand for this case is 3.2 kg/liter (258 kg/tc), low enough that a BIG/STIG cogeneration system could be used (Table 9, middle column).

Further reductions in the distillery steam use could be achieved, by reducing the distillery steam demand to 1.5 kg/liter via heat integration. The overall factory steam demand would then be about 2.8 kg/liter (223 kg/tc) (Table 9, last column), and the BIG/ISTIG cogeneration system could be used. A flow diagram for this type of factory is shown in Figure 6c. The cost of autonomous distillery equipment would be about the same for each of the cases shown in Figures 6a, 6b, and 6c.

It may be feasible to design distillation systems with even lower energy use. Heat integrated distillery designs using 1.2 kg/liter have been reported (53,56). If electricity is substituted for steam via distillery vapor recompression systems even lower steam use may be possible (53,55,57,58).

PROSPECTIVE ECONOMICS FOR THE COPRODUCTION OF ALCOHOL AND ELECTRICITY

For each of the cogeneration technologies under consideration (CEST, BIG/STIG, and BIG/ISTIG), the prospective economics are assessed here for the setup indicated in Figure 7: the distiller markets alcohol and sells cane residues to the cogenerator; and the cogenerator sells steam and electricity to the distiller and the excess electricity to the electric utility. It is assumed that during the milling season the distiller sells bagasse to the cogenerator and pays him for process steam and electricity. For the off-season, it is assumed that the cogenerator uses barbojo as fuel, purchased either from the distiller (if the distiller owns the cane) or from independent cane growers. (Of course, if barbojo recovery is not feasible or practical, an alternative fuel such as wood or oil could be used as the off-season fuel.)

Some of the alternative electricity production scenarios considered for the economic analysis are displayed in Figure 8, alongside the situation in typical existing distilleries. With CEST, BIG/STIG, and BIG/ISTIG systems operated year-round, annual electricity production would be 298 kWh/tc, 672 kWh/tc, and 733 kWh/tc, respectively, for a 160-day milling system. Since typically only about 3/5 of the barbojo is needed in the offseason, consideration might sometimes be given to shortening the milling season, thereby making it feasible to use more of the barbojo during the longer offseason. For BIG/ISTIG systems, reducing the growing season to 133 days would make it possible to use 80% of the barbojo and thereby increase electricity production to 897 kWh/tc.

Prospective costs for alcohol and cogenerated electricity[9] are summarized in Figures 9a for all the technological options considered and a 160-day milling season--the norm for Brazil. For each cogeneration option, a range of ethanol and electricity costs are shown, corresponding to different prices received by the distiller from sales of cane residues to the cogenerator. As the price of the cane residues increases (moving from left to right along each line), the

---

[9] For this analysis a real discount rate of 15% (10%) and a 20-year (30-year) plant life are assumed for distillery (cogeneration) operations, and the insurance cost is assumed to be 0.5%/yr of the initial capital cost.

cost of electricity increases and the corresponding cost of ethanol decreases, because it is assumed that the distiller takes the excess revenues as a credit against the cost of alcohol production. Two lines are shown for each cogeneration option. The top line represents the case where only bagasse revenues are credited against the alcohol production cost. This would be the case if the off-season barbojo fuel were purchased not from the distiller but from independent cane growers. The steeper line is for the case where the distiller owns the cane fields and sells barbojo as well as bagasse to the cogenerator. The point where these lines meet indicates the ethanol and electricity costs when no net payments are exchanged between the cogenerator and the distillery: bagasse is given to the cogenerator in exchange for the steam and electricity needed to run the plant.[10] The costs of the conventional energy alternatives to cane alcohol and electricity are also indicated in Figure 9a.

For fuel ethanol to be economically attractive fuel it must be competitive with other fuels. At the present world oil price ethanol would have to be priced at 15 cents/liter (line A1) or less to be competitive with gasoline as a neat fuel and 21 cents/liter or less to be competitive in gasohol (line A2).

Similarly, the cogenerated electricity must be competitive with alternative electricity supplies. If the cogeneration facility were competing against an existing oil-fired thermal power plant, the cost of the cogenerated electricity would have to be less than the <u>operating cost</u> of this plant, some 3.9 cents/kWh (line E1), based on the current residual oil price. If instead, the electrical competition were a new hydropower plant costing $1500/kW, the cost of the cogenerated electricity would have to be less than or equal to 4.3 cents/kWh (line E2). A third possibility is that the competition would be a new coal-fired steam-electric plant with flue-gas desulfurization; for an installed cost of $1400/kW and a coal price of $1.7/GJ, electricity from such a plant would cost about 5.3 cents/kWh (line E3). Still another possibility is that the cogenerator also has access to woodchips as an alternative biomass feedstock. In this case the maximum cost of cane residues to the cogenerator (purchase price plus the cost for processing the biomass into a gasifiable form) would be no greater than about $3/GJ (indicated by black dots), the estimated cost of delivered, air-dried woodchips in Brazil (59).

Figure 9a shows that under certain conditions, it would be possible to co-produce ethanol competitively with gasoline and electricity at costs competitive with other supplies:

- The low-cost conditions in Brazil for cane production and processing are key factors underlying the favorable prospective economics for alcohol

---

[10] For BIG/GT systems, the cost of processing the bagasse is estimated to be $1.25/GJ for drying and briquetting (47), which is probably needed to make the bagasse a suitable feedstock for the assumed fixed-bed gasifier; the corresponding cost for recovering, transporting, and briquetting field-dried barbojo is estimated to be $1.35/GJ (47). For CEST systems, no drying or processing would be required for bagasse, but the cost for harvesting, baling, and drying the barbojo is estimated to be $0.97/GJ (47).

indicated here. The two most important factors in reaching low ethanol costs are low cane costs[11] and low distillery capital costs.[12] If Brazilian cost conditions are met, it would be possible, without cane residue fuel credits, to produce ethanol at about 21 cents/liter--a cost low enough to make ethanol roughly competitive as an additive to gasoline. The corresponding cost of electricity production would be 5 cents/kWh or less with all the cogeneration systems considered, and less than 3 cents/kWh with the BIG/ISTIG system.

- With cane residue sales credits, it would be possible to produce hydrous ethanol at a net cost of less than 15 cents/liter, making it competitive with gasoline even at the current oil price. At these ethanol costs, gas turbine cogeneration systems (BIG/STIG or BIG/ISTIG) would be required to reach the low production costs needed for the cogenerated electricity to be competitive with other options in most places. The BIG/ISTIG system appears to be particularly promising. With BIG/ISTIG it would be possible to provide ethanol at a cost competitive with wholesale gasoline at the same time the electricity cost would be less than $0.045/kWh, even for an average cane residue price of more than $3/GJ. Electricity costs with the CEST system would probably be too high to allow this system to compete if the residue credits were high enough to make neat ethanol competitive with gasoline.

---

[11] The cost of cane delivered to the factory depends on many factors, including cane yield, the type of land, climate, the harvesting system, labor costs and transportation costs to the factory. Not surprisingly, cane growing and harvesting practices are site specific and vary considerably around the world (60,61). Accordingly, the cost of cane varies from $8/tonne in Brazil to over $20/tonne in Louisiana. The large scale of cane production in Brazil may be a factor in reaching low costs, as well as cane varieties and cultivation practices optimized for high yield (36). The prospects for reaching these low cane costs in other regions needs to be better understood.

[12] Brazilian autonomous distillery costs are typically only one half to one third those quoted by US engineering firms. Several factors could account for the difference in autonomous distillery equipment costs (50,62):

- Autonomous distillery equipment is manufactured in Brazil on a much larger scale than elsewhere, so that manufacturers achieve lower costs by taking advantage of economies of scale in production volume.
- Because of the experience gained in the PROALCOOL program, the Brazilian alcohol industry may be further along the technological "learning curve."
- Labor and/or material costs may be lower in Brazil.
- Engineering standards or codes for process equipment may be different.

Understanding these issues in detail could shed light on whether the Brazilian experience with autonomous distillery costs could be replicated elsewhere.

- The costs of ethanol and electricity are sensitive to the cane residue price. The lowest net alcohol costs are reached when the distiller can sell barbojo for off-season fuel in addition to bagasse during the milling season. In practice the price of cane residues would probably be determined by their value for nonenergy uses, by the price of competing cogeneration fuels (fuel wood or oil) or by the price of electricity from competing sources (e.g. hydropower), when they are less costly than cogenerated electricity.

- While it is likely that Brazilian alcohol distillery capital costs could be replicated in most other parts of the cane-producing world, the prospects for reducing cane costs to Brazilian levels are limited by regional climatic, labor cost, and other conditions. However with BIG/ISTIG technology, even if cane costs are as high as $20/tc, the ethanol would be competitive with gasoline at the present world oil price and the electricity would be competitive with coal-based electricity, if the distillery capital cost were the same as in Brazil and if revenues from the sale of both bagasse and barbojo could be credited against the cost of alcohol (49).

Figure 9b illustrates the economics of coproduction for a milling season shortened to 133 days to make possible greater use of the barbojo. With a shorter milling season the capacity factor for the distillery would be shortened, which would tend to increase the cost of alcohol production. But if the distiller owned the barbojo, the greater barbojo sales would tend to reduce the cost of alcohol production. A comparison of Figures 9a and 9b shows that for both the BIG/STIG and BIG/ISTIG cases the cogenerated electricity would be competitive with the alternatives at lower net alcohol costs for the shorter milling season than for the normal milling season, indicating that it would be desirable to explore the shortened milling season option for situations where the distiller owns the cane. The major unanswered question about this option is whether it would be practical to recover so much of the barbojo.[13]

GLOBAL POTENTIAL FOR CANE ENERGY AND GREENHOUSE GAS EMISSIONS REDUCTION

To give an indication of the potential role of cane energy in the global energy economy, consider a scenario where cane production grows at 3%/yr (the historical rate since 1960--Table 3) over the next 40 years, of which 1.5%/yr growth [the sugar demand growth rate projected by the World Bank for the period to 1995 (14)] is committed to sugar production and the rest to alcohol production (assuming that the favorable economic conditions for the coproduction of alcohol and electricity we identified for Brazil are generally applicable in the developing world). Further assume that all the growth in cane production

---

13 Technologies are being developed to harvest and recover barbojo (63). However, the extent to which it is practical and cost-effective to recover barbojo may be site-dependent. Studies are needed to understand the prospects for barbojo recovery under the variety of conditions that characterize the cane industry throughout the world.

takes place in developing countries. Thus, at the end of this period some 3140 million tonnes of cane would be produced there annually, of which 1430 million tonnes would be committed to alcohol production.

Suppose that by the end of this period modern cogeneration technologies are fully deployed in developing countries throughout the cane sugar and alcohol industries. Thus for an average milling season of 160 days, total electricity production in the cane industries in 2027 would be 940 TWh, 2080 TWh, or 2270 TWh for CEST, BIG/STIG, or BIG/ISTIG technologies, respectively, assuming all electricity is provided by one of these technologies. If instead the average milling season were shortened to 133 days, total electricity production would be greater--up to 2780 TWh in the case of BIG/ISTIG--a level that is 70% higher than total electricity production from all sources in the 80 sugar cane producing developing countries in 1987 (Table 12).

Suppose also that alcohol is produced at autonomous distilleries at an average rate of 70 l/tc and that methane is produced via anaerobic digestion from stillage at an average rate of 0.33 GJ/tc. Further suppose that 1.19 liters of ethanol is worth 1 liter of gasoline as a neat fuel (taking into account the modest octane-enhancing benefit of using ethanol in automotive engines). Then annual alcohol and methane production at the end of this 40-year period would be 3.3 EJ/yr (crude oil equivalent) and 0.5 EJ/yr, respectively. Ethanol and methane production in 40 years would be equivalent to 9% and 5%, respectively, of oil and gas used in all developing countries in 1987.

In estimating the potential reduction in fossil fuel CO_2 emissions arising from cane energy, suppose that the electricity produced from cane displaces electricity that would otherwise be produced from coal and that both alcohol and methane produced at distilleries displace gasoline in the transport sector. Taking into account the fossil CO_2 emissions associated with the growing, harvesting, transporting, and processing of cane for energy purposes under Brazilian conditions (Tables 13 and 14), net CO_2 emissions reduction are estimated to be 52.6 kg C/tc (82% of gross emissions reduction) for traditional cane alcohol technology, 73-220 kg C/tc (97% of gross emissions reduction) for all sugar/electricity coproduction technologies, and 116-263 kg C/tc (90-94% of gross emissions reduction) for the alcohol/electricity coproduction options (Table 13). The aggregate net emissions reduction potential for the cane industry in 2027 ranges from 0.062GT C/yr for the traditional alcohol industry, to 0.75GT/yr for BIG/ISTIG technology with a shortened growing season (Table 13). The latter is equivalent to nearly half of total emissions from fossil fuel combustion in developing countries in 1986 (Table 2).

Most of the energy and CO_2 emissions reduction arising from alcohol/electricity coproduction is associated with electricity (Table 13). However, the coproduction of alcohol and electricity would make it possible for the cane industry to expand beyond the limits set by future sugar demand growth, thereby making possible far greater overall emissions reduction than would be the case if sugar were the only coproduct of electricity from cane. Moreover, even though the direct impacts of cane alcohol on CO_2 emissions would be small compared to the impact made by cane electricity, the produced alcohol could still often play a significant role in the local energy economy as a high quality liquid fuel carrier, as has been demonstrated in Brazil, where in 1988 ethanol consumption was actually 12% greater than gasoline consumption (64).

The major uncertainty concerning the alcohol/electricity scenario presented in Table 13 is the extent to which the low-cost conditions that characterize the Brazilian alcohol industry can be replicated in other regions of the developing world. However, the overall potential for electricity production in the cane industry is probably not too sensitive to the global outlook for alcohol. If all the 3080 million tonnes per year of sugar cane production targeted for the year 2027 were used to support sugar markets instead of sugar + alcohol markets, and if all the produced sugar were marketed in developing countries, per capita sugar consumption in developing countries in 2027 would be just 45 kg/capita (assuming a developing country population of 6.85 billion then)--still only 3/4 of per capita consumption of calorific sweeteners in the US. Developing country demand for sugar tends to rise rapidly with income (14), and demand growth could be accelerated by lower sugar prices made possible through sugar/electricity coproduction strategies, just as alcohol/electricity coproduction strategies can be expected to make lower alcohol prices possible. Moreover, reduced sugar prices might even make it possible for cane sugar producers to win back some of the calorific sweetener market that has been lost to high fructose corn syrups.[14]

PUBLIC POLICY ISSUES

Deployment of BIG/GT technologies in the sugar cane industries would be a promising initial strategy for modernizing biomass as an energy source in support of broad development goals, while simultaneously helping to reduce CO_2 emissions from the burning of fossil fuels.

<u>A Developing Country Lead in Deploying BIG/GT Technologies?</u> Exploiting energy from cane in the more than 70 developing countries that grow it could help these countries reduce their energy import dependency. Moreover, the unit capital costs for BIG/GT technologies would often be considerably less than the unit capital costs of conventional, large, central-station, fossil-fuel, nuclear, or hydroelectric plants (compare Tables 6 and 15). This is especially important in light of the fact that sharply rising capital costs for electricity based on conventional technologies (Table 16) are raising the spectre of limited capital availability as a constraint on the development of developing countries (66,67). The deployment of BIG/GT technologies in rural areas would also help cope with sharply rising transmission and distribution (T&D) costs (Table 15). While most cities and towns are already electrified, many rural areas are not. It is very costly to provide initial electricity supplies to rural areas from large central-station sources, because of the low load factors on the power lines in the early stages of electrification. Considerable T&D savings could be realized by deploying decentralized BIG/GT technologies to serve rural local markets during the early stages of T&D development. Moreover, BIG/GT technologies

---

14 In the US, per capita consumption of high fructose corn syrup sweeteners rose from 0.45 kg/capita in 1970 (out of a total calorific sweetener consumption of 56 kg/capita) to 29 kg/capita in 1987 (out of a total calorific sweetener consumption of 60 kg/capita). In this same period sugar consumption declined from 46 to 28 kg per capita (65).

deployed at sugar cane factories could help provide a basis for rural industrialization and employment generation, thereby helping stem urban migration and reducing rural poverty.

Such considerations indicate that sugar cane-producing developing countries should be powerfully motivated to demonstrate and deploy BIG/GT technologies without taking into account greenhouse concerns.

However, many developing countries are unable to consider seriously major innovations relating to energy. Acting alone, they do not have the financial resources to risk on commercial demonstrations of energy technologies, strapped as they are with many immediate problems.

Moreover, countries that are capable of carrying out commercial demonstrations are usually given scant encouragement by the bilateral and multilateral assistance agencies. Rapidly industrializing countries like Brazil, for example, are too "developed" to qualify for US AID assistance, while countries that do qualify typically do not have strong enough technological infrastructures to support commercial demonstrations of technologies like the BIG/GT. Also, policies of the multilateral financial assistance agencies do not encourage technological innovations relating to energy. For example, in a 1987 speech on World Bank energy policy, a Bank official stated (68):

> "...In the world of energy, as in many other areas, [the Bank's] role is not to create innovative technical solutions, or to help countries to gamble on new processes, but to identify the best practices in a developing country situation, and encourage their wider adoption where merited by circumstances..."

Even if BIG/GT technologies were commercially available, it would be difficult to deploy them in many developing country situations without new facilitating public policies. These technologies are unfamiliar, the cane sugar and alcohol industries are not accustomed to embracing major new technologies, and the required investments would be large compared to the investments in the original sugar factories or alcohol distilleries[15]. Moreover, even if the cane industries could be persuaded to deploy BIG/GT technologies, they would often face major problems in trying to market the produced electricity. In developing countries most electric power plants are central-station facilities owned by utilities. Efforts to introduce decentralized BIG/GT cogeneration units would often be met by the same kind of resistance from utilities that cogenerators in the US faced before the adoption of the Public Utility Regulatory Policies Act of 1978 (PURPA). This legislation, which has created a cogeneration boom in the US (5), requires utilities to purchase electricity produced by qualifying cogenerators at prices which the utilities could avoid by not having to provide that power themselves and to provide backup power to these cogenerators at non-discriminatory rates. Policy changes along these lines or other approaches that

---

[15] A typical distillery in Brazil producing 120,000 liters of ethanol per day costs about $7 million installed (16). This size distillery could support a 23 MW BIG/ISTIG unit that would cost about $25 million.

would promote cogeneration and decentralized power generation more generally are probably needed to facilitate the introduction of BIG/GT technologies in developing country applications.

An Industrialized Country Lead in Deploying BIG/GT Technologies? If developing countries are not likely to take the lead in developing and deploying BIG/GT technologies, what about the already industrialized countries?

There is growing interest throughout the industrialized world in the use of high-efficiency gas turbines for power generation using natural gas as fuel, for both central station and cogeneration applications (5). But most of this activity involves the use of heavy-duty industrial gas turbines and combined cycles. While combined cycles are well-suited for power generation at scales of hundreds of megawatts, they do not offer particularly attractive economics at the much more modest scales needed for biomass applications, where various steam-injected cycles based on the use of aeroderivative turbines would be more attractive.

Because it is generally thought that natural gas may be no more abundant than oil (69) and thus must be regarded as a transition fuel, there is also considerable industrialized country interest in developing technologies will make it possible to marry the gas turbine to more abundant, lower quality fuels. Because coal is abundant and relatively cheap, ongoing R&D efforts are aimed at marrying the gas turbine to coal through coal gasification. These efforts too are focussed on combined cycle applications. There are no demonstration projects underway aimed at marrying the gas turbine to biomass through biomass gasification.

Why isn't the private sector rushing to commercialize technologies like ISTIG? For natural gas-based central station power applications ISTIG might offer an advantage of a couple of percentage points in efficiency over the best combined cycle systems on the market, but this advantage is probably not adequate to warrant bringing it to market under present conditions. Its major advantage--high efficiency and low unit cost at modest scale--though important for biomass applications, is not so important for natural gas applications. The US manufacturer that has advanced ISTIG designs has indicated a willingness to commercialize the technology without government support, provided there is sufficient commercial interest (70). But potential users are not likely to be interested in this technology unless natural gas prices are considerably higher than at present and in any case seem unwilling to commit financial resources to a technology that has not been demonstrated.

Acting alone, private companies may also not be willing at this time to develop BIG/GT technologies for developing country markets. As many developing countries have abundant, low-cost natural gas resources that are largely unexploited (5), near-term privated-sector efforts aimed at expanding the use of gas turbines for power generation in developing countries are likely to focus on these lucrative natural gas applications instead. Also, developing country debt problems, conservative developing country attitudes toward new technologies, restrictions by some developing countries on foreign investment, and other financial risks make developing country power markets less than attractive theaters for innovation by industrial country firms that would be capable of introducing BIG/GT power generating technologies.

There are also significant potential near-term industrialized country markets for BIG/GT technologies where there are substantial unused or inefficiently used residues--most notably in the pulp and paper industry (71). But again, private sector interest in these potential markets is weak at present, owing to low natural gas prices and abundant coal resources.

Toward North/South Cooperation in Deploying BIG/GT Technologies: The emergence of global warming as a paramount environmental concern could radically improve the outlook for commercializing and deploying BIG/GT technologies. The prospect that most future emissions of CO_2 will come from developing countries (Table 16) gives the industrialized countries a powerful incentive to help developing countries find ways to meet their development goals with lower CO_2 emissions than would be the case under "business-as-usual" conditions relating to energy.

While it would be neither realistic nor just to expect developing countries to put greenhouse concerns high on their public policy agenda, in light of far more pressing development challenges. However, they should be willing to pursue low greenhouse gas-emitting energy paths as long as so doing is consistent with meeting sustainable development goals and would not cost them much more than conventional energy.

Could the industrialized countries be expected to shoulder the burden of the extra costs of pursuing low CO_2-emitting energy strategies in developing countries? The extent to which they might be expected to do so depends, of course, on how large the costs are expected to be and how they compare to the expected benefits.

Unfortunately, the benefits of reducing greenhouse emissions are extraordinarily difficult (and perhaps impossible) to estimate in satisfactory ways. And some studies of the economics of reducing global CO_2 emissions suggest that the costs might be quite high. Manne and Richels estimate that a long-run equilibrium carbon tax of about $250 per tonne would be needed to constrain CO_2 emissions globally so that emissions from industrialized countries fall to 80% of the 1990 level by 2020, emissions from developing countries are constrained to double the present level, and global emissions stabilize at a level 15% higher than at present by 2030 (72). In order for developing countries to stay within these carbon emission limits without incurring extra costs, industrialized countries would have to transfer over $900 billion annually to developing countries by the middle of the next century, under the assumptions of the Manne-Richels modeling exercise.

In their modelling exercise, Manne and Richels assumed that zero CO_2 emissions could be achieved in electric power generation without increasing the cost of electricity beyond that for coal-based power generation--most likely through the use of advanced nuclear power technology. They also assumed that zero CO_2-emitting non-electric energy supplies would cost twice as much ($19/GJ) as synthetic fuels from coal ($9.5/GJ) that are characterized by a CO_2 emissions rate of 0.0387 tonnes C/GJ. It is the latter assumption that led to their estimated equilibrium carbon tax:

$$(\$19 - \$9.5)/0.0387 = \$250\text{/tonne of carbon.}$$

The present study indicates that sugar cane-based bioenergy strategies would reduce CO_2 emissions at much lower marginal costs than is indicated by the Manne-Richels study.

Even without the economic benefits of coproduction, the production cost for alcohol in Brazil ($0.21/liter or $8.9/GJ--Figure 9a) would be slightly less than the cost of synfuels from coal. Since net fossil fuel-based carbon emissions associated with alcohol production is 9.6 kg C per tonne of cane (Table 13) or 0.0058 tonnes C/GJ of alcohol (assuming no credit for the production of methane from stillage), the cost of carbon removal associated with producing ethanol from cane as an alternative to producing coal-derived synfuels would be negative:

$$(\$8.9 - \$9.5)/(0.0387 - 0.0058) = -\ \$18\text{/tonne of carbon.}$$

With coproduction strategies the cost of carbon emissions reduction would be even more strongly negative. Consider the alcohol/electricity coproduction case (with a 160-day milling season) where the distiller sells both bagasse and barbojo to the cogenerator, at a price sufficient to reduce the net alcohol cost to 15 cents/liter--the cost needed for alcohol to be able to compete as a neat fuel with gasoline at the present world oil price. At this level the estimated cost for the 721 kWh/tc of electricity cogenerated with BIG/ISTIG (Table 13) would be 3.6 cents/kWh, compared to 5.3 cents/kWh for a coal plant (Figure 9a), so that the cost of reducing carbon emissions by 0.222 tonnes per tonne of cane processed (Table 14) for this coproduction strategy would be:

$$(721\text{ kWh/tonne of cane})*[(\$0.036 - \$0.053)\text{/kWh}]/(0.222\text{ tonnes C/tonne of cane})$$

$$= -\ \$55\text{/tonne of carbon.}$$

Since these carbon emissions reduction costs are negative, achieving large emissions reductions by deploying BIG/GT technologies in the sugar cane industries would not require large transfer payments to developing countries. Rather industrialized country commitments are needed to bring to commercial readiness the gas turbine technologies involved and to work with developing countries to facilitate the transfer of these technologies to the marketplace.

It is estimated that a 20 MW commercial demonstration project for BIG/STIG would cost about $50 million--twice the estimated cost of a commercial unit (44). The estimated cost of a 110 MW demonstration project for ISTIG (with natural gas firing) is about $100 million (7).

Successful demonstrations of these technologies could lead to widespread deployment of BIG/ISTIG technology in the cane sugar industries beginning near the turn of the century and subsequently evolving along the lines depicted for the BIG/ISTIG scenarios described in Table 12. The present (1990) value of the direct economic benefits of such a course, over the period 1997-2027, would be more than $8 billion, corresponding to a benefit/cost (B/C) ratio of more than 50:1 for this $150 million investment, without taking into account any greenhouse benefits.[16]

Such a high B/C ratio suggests that there would be major advantages to both sides from North/South cooperation aimed at facilitating the introduction of BIG/GT technologies for cogeneration applications in the sugar cane industries.

A new industry involving North/South joint ventures could be spawned for marketing BIG/GT technologies, with aircraft engine manufacturers providing the gas turbines and a wide range of other companies providing much of the rest of the needed equipment.[17]

To the extent that Brazilian conditions for alcohol production prove to be relevant for other parts of the world, the already large global market for

---

[16] Consider first the situation where the average cane processing facility at which BIG/ISTIG plants would be sited has a throughput of 325 tc/hour, which could support a 111 MW BIG/ISTIG unit. Assuming that half of the cane is associated with BIG/ISTIG cogeneration technologies deployed at sugar factories and alcohol distilleries operated on 160-day milling seasons (with the alcohol producers selling only bagasse to the cogenerator) and half deployed at sugar factories and alcohol distilleries operated on 133-day milling seasons (with the alcohol producers selling both bagasse and barbojo to the cogenerator), the average cost of electricity (with alcohol selling for 15 cents/liter) would be 3.4 cents/kWh, compared to 5.3 cents/kWh for the coal-based electricity displaced. If total BIG/ISTIG capacity in the cane industries expands from 1 GW in 1997 (producing 7.34 TWh) to 337 GW in 2027 (producing 2473 TWh), the value of the discounted electricity cost savings (1997-2027) would be $27 billion in 1997 or $14 billion in 1990, assuming a 10% discount rate.

This assessment would apply to a situation where there would be considerable centralization of cane processing compared to the present situation--which may well take place, in order to capture the scale economies associated with coproduction. While there are many cane processing facilities in various parts of the world with throughputs well in excess of 325 tc/hour, the average throughput per factory today is instead about 100 tc/hour, which could support a BIG/ISTIG capacity of about 35 MW. At this average capacity, the cost of BIG/ISTIG electricity would be about 4.1 cents/kWh, so that the present value of the benefits would be $8.8 billion instead of $14 billion.

[17] Most of the cost associated with BIG/STIG and BIG/ISTIG systems (Table 7) is associated with "low-technology" components (gasifier, electrical generator, heat recovery steam generator, power turbine, etc.) that could eventually be manufactured by many firms in rapidly industrializing countries. The only "high-technology" component (which would have to be imported by developing country users) is the jet engine from which the gas turbine is derived. The jet engine upon which the 53 MW BIG/STIG and 111 MW BIG/ISTIG units are based (Table 6) sells for $6 million (5). It thus represents only 11% (7%) of the total installed cost of the BIG/STIG (BIG/ISTIG). By choosing high performance systems, developing countries that get involved in joint ventures to produce BIG/GT technologies could reduce foreign exchange requirements to very low levels.

sugar/electricity coproduction could be greatly expanded to an even larger global market that includes alcohol/electricity coproduction as well. Thus Brazilian producers of cane alcohol technology might wish to team up with BIG/GT manufacturers in joint ventures to serve such markets. Brazil could thus become a leading marketer of "greenhouse-safe" energy technologies.

Because of the low efficiency of photosynthesis and the high water requirements for the growing of biomass, bioenergy strategies will eventually be limited by land and water availability constraints and thus by themselves do not offer "the" solution to the problem of global warming. But by using high efficiency conversion technologies like the BIG/GT technologies considered here, these constraints can be pushed far into the future, and much can be accomplished by deploying these technologies in sugar cane and other residue markets (8,71) and eventually in markets served by dedicated biomass plantations (9).

Joint North/South initiatives relating to BIG/GT technologies would seem to be consistent with the US Administration's "no regrets" policy on climate change, by which is meant, according to Secretary of State Baker (73), that:

> "...we are prepared to take actions that are fully justified in their own right and which have the added advantage of coping with greenhouse gases. They're precisely the policies we will never have cause to regret."

ACKNOWLEDGMENTS

For research support the authors thank the Office of Energy of the US Agency for International Development, the US Environmental Protection Agency, the New Land Foundation, and the Merck Fund.

For useful discussions the authors thank Pedro Assis, Luiz Paulo de Biase, Harold Birkett, Carlos de Camargo, Stephen Clarke, Stefano Consonni, Michael Hylton, William Keenliside, Eric Larson, Alistair Lloyd, Isaias Macedo, Jose Roberto Moreira, Jose Campanari Neto, Jose Luis Oliverio, Alice de Ribeiro, Jose Valdir Sartori, Francis Schaeffer, Gil Serra, Walter Siebold, Robert Socolow, Charles Weiss, and Florenal Zarpelon.

REFERENCES

1. Office of Technology Assessment, Energy from Biological Processes, Washington, DC, 1980.

2. US Environmental Protection Agency, "Policy Options for Stabilizing the Global Climate," February 1989 (draft).

3. David O. Hall, private communication. See also Hall, Barnard, and Moss, Biomass for Energy in Developing Countries, Pergamon Press, 1982.

4. Robert H. Williams, "Potential Roles for Bioenergy in an Energy-Efficient World," Ambio, vol. 14, nos. 4-5, pp. 201-209, 1985.

5. R.H. Williams and E.D. Larson, "Expanding Roles for Gas Turbines in Power Generation," in Electricity, T.B. Johansson, B. Bodlund, and R.H. Williams, eds., University of Lund Press, Lund, Sweden, 1989.

6. S.B. Alpert and M.J. Gluckman, "Coal Gasification Systems for Power Generation," Electric Power Research Institute, Palo Alto, California, 1986.

7. J.C. Corman, "System Analysis of Simplified IGCC Plants," report prepared for the US Dept. of Energy by the Corporate R&D Center, the General Electric Company, Schenectady, NY, September, 1986.

8. E.D. Larson, P. Svenningsson, and I. Bjerle, "Biomass Gasification for Gas Turbine Power Generation," in Electricity, T.B. Johansson, B. Bodlund, and R.H. Williams, eds., University of Lund Press, Lund, Sweden, 1989.

9. R.H. Williams, "Biomass Gasifier/Gas Turbine Power and the Greenhouse Warming," in Energy Technologies for Reducing Emissions of Greenhouse Gases, vol. 2, pp. 197-248, Proceedings of an Experts' Seminar, OECD/IEA, Paris, 12th-14th April, 1989.

10. Food and Agriculture Organization of the United Nations, FAO Production Yearbook, vol. 41, FAO Statistical Series No. 82, 1987.

11. C.E. Wyman and N.D. Hinman, "Ethanol: Fundamentals of Production from Renewable Feedstocks and Use as a Transport Fuel," Solar Energy Research Institute, Golden, Colorado, 1989.

12. S. Hochgreb, "Methane Production from Stillage," COMGAS, Sao Paulo, 1985.

13. Robert D. Perlack and J. Warren Ranney, "Economics of Short-Rotation Intensive Culture for the Production of Wood Energy Feedstocks," Energy, vol. 12, no. 12, pp. 1217-1226, 1987.

14. James G. Brown, "The International Sugar Industry: Developments and Prospects," World Bank Staff Commodity Working Paper No. 18, March 1987.

15. "Agroindustria Canavieira: Um Perfil," Copersucar, Sao Paulo, Brazil,

Countries, Vienna, Austria, March 26-30, 1979.

29. J.G. da Silva, G.E. Serra, J.R. Moreira, J.C. Concalves, and J. Goldemberg, "Energy Balance for Ethyl Alcohol Production from Crops," Science, vol. 201, pp. 903-906, September 8, 1978.

30. C.S. Hopkinson and J.W. Day, "Net Energy Analysis of Alcohol Production from Sugarcane," Science, vol. 207, pp. 302-304, January 18, 1990.

31. J.A. Polack, H.S. Birkett, and M.D. West, "Sugar Cane: Positive Energy Source for Alcohol," Chemical Engineering Progress, June 1981.

32. Copersucar, Proalcool: Fundamentos e Perspectivas, Sao Paulo, 2nd Edition, September, 1989.

33. Office of Technology Assessment, "Gasohol," A Technical Memorandum, Washington, DC, September 1979.

34. E. Hugot, Handbook of Cane Sugar Engineering, Elsevier Science Publishing Company, New York, NY, 1986.

35. C.A. de Camargo, "Balanco de Vapor e Conservacao de Energia em Usinas e Destilarias," Brazil Acucareiro, Rio de Janeiro, v. 105, pp.44-53, 1987.

36. G. Serra, University of Sao Paulo, Campinas, Brazil, private communications, 1989.

37. J.C. Neto, Copersucar Technical Center, Piracicaba, Brazil, private communications, 1989.

38. J.L. Oliverio, J.D. Neto, and J.F.P. de Miranda, "Energy Optimization and Electricity Production in Sugar Mills and Alcohol Distilleries," Proceedings 20th Congress of the International Society of Sugar Cane Technologists, Sao Paulo, Brazil, October 12-21, 1989.

39. J.L. Oliverio and R.J. Ordine, "Novas Tecnologias e Processos que Permitam Elevar o Excedente de Bagaco das Usinas E Destilarias," Brazil Acucareiro, Rio de Janeiro, v. 105, pp.54-88, 1987.

40. "Tecnicas para Producao de Excendentes de Bagacao," Copersucar, Sao Paulo, 1986.

41. C.A. Camargo, A.M. de Melo Ribeiro, "Manual of Energy Conservation in the Cane Sugar and Alcohol Industry," IPT Report, Instituto de Pesquisas Tecnologias de Etsado de Sao Paulo, Sao Paulo, Brazil, 1989.

42. C. Kinoshita, Hawaiian Sugar Planters Association, private communications, 1987.

43. Commission of the European Communities, "24.65 MW Bagasse Fired Steam Power Demonstration Plant," Report No. EUR 10390 EN/FR, 1986.

1989; "PROALCOOL," Copersucar, Sao Paulo, Brazil, 1989.

16. J. Goldemberg, J.R. Moreira, P.U.M. Dos Santos, and G.E. Serra, "Ethanol Fuel: A Use of Biomass Energy in Brazil," Ambio, vol. 14, no. 4-5, 1985; G. Serra and J.R. Moreira, University of Sao Paulo, Brazil, private communications, 1989.

17. H. Geller, "Ethanol Fuel from Sugar Cane in Brazil," Annual Review of Energy, vol. 10, pp. 134-164, 1985.

18. H. Steingass, K. Wentzel, M. Kappaz, F. Schaeffer, R. Schwandt and P. Bailey, "Electricity and Ethanol Options in Southern Africa," Office of Energy, Bureau for Science and Technology, USAID, Report No. 88-21, September 1988.

19. "Worldwide Review of Biomass Based Ethanol Activities," Meridian Corporation Report, Contract No. MC-JC-85FB-008, 1985.

20. "Power Alcohol in Kenya and Zimbabwe - A Case Study of the Transfer of a Renewable Energy Technology," United Nations Trade and Development Board Report, GE.84-55979, June 5, 1984.

21. M.G. Hylton, Director, Factory Technology Division, Sugar Industry Research Institute, Kingston, Jamaica, private communications, 1989.

22. W.V. Saunders, "Petroleum Company of Jamaica's Ethanol Project - An Update," Proceedings of the Jamaican Society of Sugar Technologists, Ocho Rios, Jamaica, November 5, 1987.

23. "Alcohol Production from Biomass in the Developing Countries," World Bank Report, September 1980.

24. A. Jacobs, F. Tugwell, H. Steingass, M. Alvarez, F. Arechaga, W. Klausmeier, R. Richman, "Fuel Alcohol Production in Honduras: A Technical and Economic Analysis," USAID Cane Energy Program, April 1986.

25. "The Sugar Industry in the Philippines," USAID Cane Energy Program, December 1986.

26. "The AID Approach: Using Agricultural and Forestry Wastes for the Production of Energy in Support of Rural Development," USAID Bioenergy Systems Report, April 1989.

27. F.C. Schaeffer and Associates, "Evaluation and Technical and Financial Assessment, Central Azucerera Tempisque, S.A. (CATSA)," Report to CODESA/USAID, Volume 1, July 1987.

28. J.R. Moreira, V.R. Vanin, and J. Goldemberg (Institute of Physics, University of Sao Paulo, Sao Paulo, Brazil), "Energy Balance for the Production of Ethyl and Methyl Alcohol," presented at the Workshop on Fermentation Alcohol for Use as Fuel and Chemical Feedstock in Developing

44. J.C. Corman, "Integrated Gasification Steam-Injected Gas Turbine (IG-STIG", presentation at the Workshop on Biomass-Gasifier Steam Injected Gas Turbines for the Cane Sugar Industry, Washington, DC, organized by the Center for Energy and Environmental Studies, Princeton University, June 12, 1987.

45. E.D. Larson and R.H. Williams, "Biomass Gasifier Steam-Injected Gas Turbine Cogeneration," Journal of Engineering for Gas Turbines and Power, vol. 112, pp. 157-163, April, 1990.

46. J.M. Ogden, S. Hochgreb and M. Hylton, "Process Energy Efficiency and Cogeneration in Cane Sugar Factories," Proceedings 20th Congress of the International Society of Sugar Cane Technologists, Sao Paulo, Brazil, October 12-21, 1989.

47. E.D. Larson, J.M. Ogden, R.H. Williams, " Steam-Injected Gas Turbine Cogeneration for the Cane Sugar Industry," Princeton University, Center for Energy and Environmental Studies Report No. 217, September 1987.

48. E.D. Larson, R.H. Williams, J.M. Ogden and M.G. Hylton, "Biomass-Fired Steam-Injected Gas Turbine Cogeneration for the Cane Sugar Industry," Proceedings 20th Congress of the International Society of Sugar Cane Technologists, Sao Paulo, Brazil, October 12-21, 1989.

49. J.M. Ogden and M.E. Fulmer, "Assessment of New Technologies for Co-Production of Alcohol, Sugar, and Electricity from Sugar Cane," Center for Energy and Environmental Studies, Princeton University, draft report, February 1990.

50. H.S. Birkett, F.C. Schaeffer and Associates, Baton Rouge, LA, private communications, 1989.

51. J.C. Teixeira da Silva, Manager, Department of Product and Process Development, Dedini, S.A., Sao Paulo, Brazil, private communications, 1987; Quotes from Brazilian manufacturers Dedini, Zanini, private communications, 1988, 1989.

52. US Dept. of Energy, "Assessment of Costs and Benefits of Flexible and Alternative Fuel Use in the US Transportation Sector; Technical Report Three: Methanol Production and Transportation Costs," draft, August 29, 1989.

53. A. Serra, M. Poch and C. Sola, "A Survey of Separation Systems for Fermentation Ethanol Recovery," Process Biochemistry, October 1987, p.154-158.

54. G. Parkinson, "Batelle Maps Ways to Pare Ethanol Costs," Chemical Engineering, June 1, 1981.

55. L.R. Lynd and H.E. Grethlein, "IHOSR/Extractive Distillation for Ethanol Separation," Chemical Engineering Progress, November 1984, pp. 59-62.

56. R. Katzen, et.al., "Low Energy Distillation Systems," in Bioenergy '84, vol. 1, p. 309.

57. "Heat Pumps in Distillation," EPRI Report, 1986.

58. Perry's Chemical Engineers' Handbook, McGraw Hill Co., New York, NY, Chapter 13, 1984.

59. V.I. Suchek, Director, Division of Development, Jaako Poyry Engineering, Sao Paulo, Brazil, private communications, 1989.

60. D.H. West, "A Cost Analysis Programme for Mechanical Harvesting of Sugar Cane," 23rd West Indies Sugar Technologists Conference, Bridgetown, Barbados, April 17-22, 1988.

61. C. Hudson, Symposium on "Mechanical Harvesting Systems for Cane," presented at the 20th Congress of the International Society of Sugar Cane Technologists, Sao Paulo, Brazil, October 1989.

62. J.M. Paturau, "Is Ethanol the Fuel of the Future for Sugar Cane Producing Territories," Proceedings 18th Congress of the International Society of Sugar Cane Technologists, 1980.

63. Ronco Consulting Company and Bechtel National, Inc., "Jamaican Cane Energy Project Feasibility Study," a report of the Office of Energy, US Agency for International Development and the Trade and Development Program, Washington, DC, 1986.

64. Ministerio das Minas Energia, Boletim do Balanco Energetico Nacional 1989, Brasilia, Brazil, 1989.

65. Bureau of the Census, Statistical Abstract of the United States, US GPO, Washington, DC, 1989.

66. R.H. Williams, "Are Runaway Energy Capital Costs a Constraint on Development? A Demand Analysis of the Power Sector Capital Crisis in Developing Countries," paper presented at the International Seminar on the New Era in the World Economy, The Fernand Braudel Institute of World Economics, Sao Paulo, Brazil, August 31-September 2, 1988.

67. US Agency for International Development, Power Shortages in Developing Countries: Magnitudes, Impacts, Solutions, and the Role of the Private Sector, a report to the US Congress, Washington, DC, 1986.

68. E.S. Daffern, "World Bank Policy in the Promotion of Energy-Producing Projects in Developing Countries," paper presented in Reading, England, April 7, 1987.

69. C.D. Masters et al., "World Resources of Crude Oil, Natural Gas, Natural Bitumen, and Shale Oil," presented at the Twelfth World Petroleum Congress, Houston, Texas, 1987.

70. "New NOx and CO Limits Spark Utility Interest in I-STIG," Gas Turbine World, vol. 18, no. 6, December 1988.

71. E.D. Larson, "Prospects for Biomass-Gasifier Gas Turbine Cogeneration in the Forest Products Industry: A Scoping Study," PU/CEES Working Paper No. 113, February 1990.

72. A.S. Manne (Stanford University) and R.G. Richels (Electric Power Research Institute), "Global CO2 Emission Reductions--the Impacts of Rising Energy Costs," preliminary draft, February 1990.

73. Secretary William Baker, "Diplomacy for the Environment," Current Policy No. 1254, Bureau of Public Affairs, United States Department of State, Washington, DC, February 26, 1990.

Table 1. Role of Bioenergy in Reducing CO2 Emissions in the US EPA Global Energy Scenarios[a]

	Global Fossil Fuel-Derived Carbon Dioxide Emissions (billion tonnes of carbon per year)		
Scenario	1985	2025	2050
RCWP	5.1	5.5	5.1
RCWP w/o Bioenergy[b]	5.1	8.6	11.1
RCW	5.1	10.3	15.3
RCW w/o Bioenergy[c]	5.1	10.5	16.5

a In 1989 the US Environmental Protection Agency carried out a major study to assess long-term energy strategies for reducing greenhouse gas emissions [US Environmental Protection Agency, "Policy Options for Stabilizing the Global Climate," February 1989 (draft)]. Alterative global energy scenarios were constructed as part of this exercise. Indicated here are variations on the EPA scenarios involving rapid economic growth. The reference case is the Rapidly Changing World (RCW) scenario. For the same economic growth conditions a Rapidly Changing World with Policy (RCWP) scenario was also constructed. The RCWP scenario differs from the RCW scenario in that it involves promoting via public policy measures various energy demand side and supply side measures to reduce carbon dioxide emissions.

b This shows what carbon dioxide emissions would be if coal were used instead of bioenergy in the RCWP scenario.

c This shows what carbon dioxide emissions would be if coal were used instead of bioenergy in the RCW scenario.

Table 2. Energy Use in and Fossil Fuel CO_2 Emissions from Developing Countries[a]

	1980	1986	Growth Rate (%/yr, 1980-86)
Electricity[b] (TWh)			
Coal	357.8	647.5	10.39
Oil	376.6	415.7	1.66
Natural Gas	80.1	151.8	11.24
Fossil Subtotal	814.5	1215.0	6.89
Hydro	444.9	603.2	5.20
Nuclear	16.2	72.6	28.40
Totals	1275.6	1890.8	6.78
Fuels (EJ)			
Coal	18.69	21.97	2.72
Oil	25.04	28.26	2.03
Natural Gas	4.90	7.25	6.76
Totals	48.64	57.48	2.85
Primary Energy (EJ)			
Coal	23.46	30.61	4.53
Oil	30.07	33.80	1.97
Natural Gas	5.96	9.27	7.64
Hydro	4.87	6.63	5.20
Nuclear	0.18	0.80	28.40
Totals	64.54	81.11	3.88
CO_2 Emissions[c] (Megatonnes C)			
Electricity			
Coal	117.3	212.6	10.39
Oil	99.9	110.3	1.66
Natural Gas	14.4	27.4	11.24
Totals	231.6	350.3	7.14
Fuels			
Coal	459.9	540.3	2.72
Oil	498.4	562.4	2.03
Natural Gas	66.1	97.8	6.76
Totals	1024.9	1200.5	2.67
Primary Energy			
Coal	577.2	752.9	4.53
Oil	598.3	672.7	1.97
Natural Gas	80.5	125.2	7.64
Totals	1256.0	1550.8	3.58

a Source: Energy Information Administration, "International Energy Annual 1988," DOE/EIA-0219(88), Washington, DC, November 1989.

b The distribution of thermal power generation by fuel is from S. Meyers and C. Campbell, "Regional Electricity Supply and Consumption in Developing Countries, 1980-1986," Database Report, Lawrence Berkeley Laboratory, March 1989.

c Emission rates are assumed to be 24.6, 19.9, and 13.5 Megatonnes C per EJ for coal, oil, and natural gas, respectively.

Table 3. Historical Data on World Sugar Cane Production[a]

	Harvested Area (million ha)	Yield[b,c] (tc/ha/yr)	Production[b] (million tc)
1987	16.56	58.44	967.9
1986	15.82	58.77	929.7
1985	15.87	58.44	927.3
1984	15.90	58.87	935.8
1983	15.43	58.12	896.9
1982	15.09	58.82	887.7
1981	13.78	57.24	788.8
1980	13.24	54.54	721.9
1979	13.58	55.55	754.5
1978	13.30	57.31	762.1
1977	13.34	55.13	735.6
1976	12.71	54.43	691.6
1975	12.35	53.47	660.5
1974	12.15	53.88	654.9
1961-65	9.52	49.39	470.1

a Source: FAO, Production Yearbook, various years.

b This is the harvested wet weight, which does not include the weight of the barbojo (tops and leaves).

c There is considerable variation in average yield from country to country. The average yield for some countries (Egypt, Malawi, Swaziland, Zambia, Zimbabwe, Peru) is about twice the global average.

Table 4. Fuel Ethanol Production from Sugar Cane (million liters/yr)

South America	
Brazil[a]	11,700
Argentina[b]	380
Paraguay[b]	26
Colombia[b]	38
Central America and Caribbean	
Costa Rica[b]	31
El Salvador[b]	15
Guatemala[b]	0.2
Jamaica[d]	15
Africa	
Kenya[c,e]	18
Malawi[c]	11
Zimbabwe[c,e]	42
Mali[b]	2
Asia and Oceania	
Thailand[b]	203
Phillipines[b]	10
New Zealand[b]	15

a For the 1988/1989 season. "Agroindustria Canavieira: Um Perfil," Copersucar, Sao Paulo, Brazil, 1989.

b 1984 ethanol production capacity installed. "Worldwide Review of Biomass Based Ethanol Activities," Meridian Corporation Report, Contract No. MC-JC-85FB-008, 1985.

c "Electricity and Ethanol Options in Southern Africa," USAID Office of Energy Report, September 1988.

d A 180,000 liter/day distillery was installed in 1988, and the planned production is 15 million liters/year. To date only about one million liters have been produced due to uncertain market conditions. (M.G. Hylton, Jamaican Sugar Industry Research Institute, Bernard Lodge, Jamaica, private communications, 1990).

e Capacity installed as of 1984. "Power Alcohol in Kenya and Zimbabwe-- A Case Study om the Transfer of a Renewable Energy Technology," United Nations Trade and Development Board Report GE.84-55979, June 5, 1984.

Table 5. Estimated Performance of Biomass-Fired Cogeneration Systems

	COGENERATION						POWER ONLY			
	Electricity		Steam		Fuel[c]	Cane	Electricity		Fuel[c]	Cane
	(MW)	(% of fuel[d])	(T/H)	(% of fuel[d])	(T/H)	(T/H)	(MW)	(% of fuel[d])	(T/H)	(T/H)
CEST[a,b]										
Generic	17.5	13.0	65.6	35.9	50.8	169	27.0	20.3	50.2	167
Generic	6.1	11.4	26.4	36.4	20.2	67	10.0	17.8	21.2	71
Generic	1.8	10.1	9.0	37.2	6.73	22	3.0	15.7	7.22	24
BIG/STIG[b]										
LM-5000	38.8	31.3	47.7	30.0	27.6	157	53.0	35.6	33.0	188
LM-1600	15.0	29.8	21.8	33.8	11.2	65	20.0	33.0	13.2	75
GE-38	4.0	29.1	5.7	32.4	3.06	17	5.4	33.1	3.63	21
BIG/ISTIG[d]										
LM-8000	97	37.9	76.2	25.4	57.7	328	111.2	42.9	57.3	325

a Adapted from E.D. Larson and R.H. Williams, "Biomass Gasifier Steam-Injected Gas Turbine Cogeneration," Journal of Engineering for Gas Turbines and Power, vol. 112, pp. 157-163, April 1990, except that here the gasifier efficiency for biomass is assumed to be the same as for coal.

b For 6.3 MPa, 482 °C steam at the turbine inlet.

c It is assumed that the BIG/STIG and BIG/ISTIG use briquetted bagasse or barbojo (15% moisture), with a higher heating value of 16,166 kJ/kg, and that the CEST uses bagasse (50% moisture) with a higher heating value of 9530 kJ/kg. It is further assumed that 300 kg of bagasse (50% moisture) are produced per tonne of cane milled. If briquetting is required the corresponding quantity would be 176 kg (15% moisture).

d Output, in energy units, as a percentage of the higher heating value of the fuel input.

e Preliminary estimate of steam and electricity production, based on performance with coal.

Table 6. Estimated Capital and Operating Costs for Biomass-Fired Cogeneration Systems

	Capacity (MW)	Installed Cost ($/kW)	Maintenance[b] Fixed (1000$/yr)	Maintenance[b] Variable ($/kWh)	Labor[b,c] (1000$/yr)
CEST[a]					
Generic	27.0	1556	664	0.003	129.6
Generic	10.0	2096	246	0.003	97.2
Generic	3.0	3008	73.8	0.003	97.2
BIG/STIG[a,d]					
LM-5000	53.0	990	1304	0.001	297.0
LM-1600	20.0	1230	492	0.001	108.0
GE-38	5.4	1650	133	0.001	97.2
BIG/ISTIG					
LM-8000	111.2[e]	770[e]	2736	0.001	405.0

a Adapted from E.D. Larson and R.H. Williams, "Biomass Gasifier Steam-Injected Gas Turbine Cogeneration," Journal of Engineering for Gas Turbines and Power, vol. 112, pp. 157-163, April 1990.

b Appendix D in E.D. Larson, J.M. Ogden, R.H. Williams, " Steam-Injected Gas Turbine Cogeneration for the Cane Sugar Industry," Princeton University, Center for Energy and Environmental Studies Report No. 217, September 1987, and E.D. Larson, private communication, 1990.

c For Jamaican labor conditions.

d In general, the estimated unit cost is $2371*MW^{-0.22}$, where MW is the installed capacity in MW. (See E.D. Larson and R.H. Williams, "Biomass Gasifier Steam-Injected Gas Turbine Cogeneration.")

e See Table 7. In general, the estimated unit cost is $2167*MW^{-0.22}$, assuming the same scaling law applies to both BIG/STIG and BIG/ISTIG technologies.

Table 7. Estimated Installed Capital Cost for IG/STIG and IG/ISTIG Power Plants Fueled with Coal and Biomass (in 1986$/kW)

	CIG/STIG[a]	BIG/STIG[b,c]	CIG/ISTIG[a]	BIG/ISTIG[b,d]
I. Process Capital Cost				
Fuel Handling	39.6	39.6	36.7	36.7
Blast Air System	13.5	13.5	9.6	9.6
Gasification Plant	160.9	160.9	83.1	83.1
Raw Gas Physical Clean-up	8.8	8.8	7.7	7.7
Raw Gas Chemical Clean-up	175.9	0.0	150.9	0.0
Gas turbine/HRSG	294.4	294.4	256.4	256.4
Balance of Plant				
Mechanical	40.2	40.2	22.0	22.0
Electrical	65.0	65.0	48.4	48.4
Civil	65.5	65.5	60.7	60.7
SUBTOTAL	862.9	687.0	686.5	535.6
II. Total Plant Cost				
Process Plant Cost	862.9	687.0	686.5	535.6
Engineering Home Office (10%)	86.3	68.7	68.6	53.6
Process Contingency (6.2%)	53.6	42.6	42.5	33.2
Project Contingency (17.4%)	150.4	119.5	119.6	93.2
SUBTOTAL	1153.2	917.8	917.2	715.6
III. Total Plant Investment				
Total Plant Cost	1153.2	917.8	917.2	715.6
AFDC (1.8%, 2 yr construction)	20.8	16.5	16.5	12.9
SUBTOTAL	1174.0	934.3	933.7	728.5
IV. Total Capital Requirement				
Total Plant Investment	1174.0	934.3	933.7	728.5
Preproduction Costs (2.8%)	32.3	26.2	26.2	20.4
Inventory Capital (2.8%)	32.3	26.2	26.2	20.4
Initial Chemicals, Catalysts	2.5	0.0	2.3	0.0
Land	1.3	1.3	1.3	1.3
TOTAL	1242	988	990	771

---

[a] J.C. Corman, "System Analysis of Simplified IGCC Plants," report prepared for the US Dept. of Energy by the Corporate R&D Center, the General Electric Company, Schenectady, NY, September, 1986.

[b] It is assumed that BIG/STIG (BIG/ISTIG) costs are the same as CIG/STIG (CIG/ISTIG) costs, except that the raw gas chemical clean-up phase required for coal would not be needed for biomass, because of its lower sulfur content.

[c] For a 53 MW unit.

[d] For a 111 MW unit.

Table 8. Estimated Capital and Operating Costs for an Autonomous Distillery Milling (excluding the costs for boilers and generating equipment), based on Brazilian Experience[a,b]

Total Installed Capital Cost (million $)	$18.083
Fixed Operating Costs (thousand $/yr)	
Labor	560
Maintenance	362
Supply	36
Insurance	90
Total	1,048
Cane Cost ($/tc)	8.07
Other Variable Costs ($/tc)	0.176

---

a For a distillery processing 4000 tonnes of cane per day and producing 73 liters of ethanol per tonne of cane.

b Source: J. Goldemberg, J.R. Moreira, P.U.M. Dos Santos, and G.E. Serra, "Ethanol Fuel: A Use of Biomass Energy in Brazil," Ambio, vol. 14, no. 4-5, 1985; G. Serra and J.R. Moreira, University of Sao Paulo, Brazil, private communications, 1989.

Table 9. Steam and Electricity Demands in Conventional and Steam-Conserving Autonmous Distilleries With Cogeneration[a]

	Conventional[b]	Steam-Conserving I[b]	Steam-Conserving II
Moderate-Pressure Steam (2.1 MPa, 300°C)			
Total steam used	466 kg/tc	258 kg/tc	223 kg/tc
Cane mills	226 kg/tc	226 kg/tc	223 kg/tc
Back-pressure steam turbines[c]	175 kg/tc	32 kg/tc	-
Throttled to low pressure	65 kg/tc	-	-
Total exhaust steam available	466 kg/tc	258 kg/tc	223 kg/tc
Low-Pressure Steam (mill and turbine exhaust @ 0.25 MPa, 127°C, saturated)			
Total steam used	454 kg/tc	258 kg/tc	223 kg/tc
Evaporator	61 kg/tc	97 kg/tc	97 kg/tc
Direct to Juice Heaters	130 kg/tc	-	-
Distillation	256 kg/tc	155 kg/tc	120 kg/tc
De-Aerator	8 kg/tc	6 kg/tc	6 kg/tc
Electricity Demand (pumps, fans)	12.5 kWh/tc	12.5 kWh/tc	12.5 kWh/tc
Electricity Production			
Factory steam turbines	12.5 kWh/tc	2.3 kWh/tc	-
w/CEST Cogeneration system	92 kWh/tc	123 kWh/tc	129 kWh/tc
w/BIG/STIG Cogeneration system	-	252 kWh/tc	256 kWh/tc
w/BIG/ISTIG Cogeneration system	-	-	298 kWh/tc
Maximum Electricity for Export	92 kWh/tc (CEST)	242 kWh/tc (BIG/STIG)	286 kWh/tc (BIG/ISTIG)

a For a distillery processing 125 tonnes cane/hour and producing 80 liters of alcohol per tonne of cane.

b Steam use is based on J.L. Oliverio, J.D. Neto and J.F.P. de Miranda, "Energy Optimization and Electricity Production in Sugar Mills and Alcohol Distilleries," presented at the 20th Congress of the International Society of Sugar Cane Technologists, Sao Paulo, Brazil, October 12-21, 1989.

c Assuming 14 kg steam/kWh.

Table 10. Design Options for the Co-production of Electricity and Alcohol From Sugar Cane at Autonomous Distlleries

Cogeneration System	Condensing Extraction Steam Turbine (CEST)	
	Steam-Injected Gas Turbine (BIG/STIG)	
	Intercooled Steam-Injected Gas Turbine (BIG/ISTIG)	
Fuel		
In-season:	Bagasse	
	Unprocessed (50% moisture) for CEST	
	Briquetted (15% moisture) for BIG/STIG and BIG/ISTIG	
Off-season:	Barbojo, wood or oil	
Cane Milling		
	Steam turbine drive	
	Electric drive	
	Diffuser	
Juice Processing		
	Conventional	Steam-Conserving
Juice Heaters:	Steam/vapor	Condensate
Evaporators:	Short Tube Rising Film	Falling Film or Falling Film/w Mechanical Vapor Recompression
Fermentation		
	Batch	
	Continuous	
Distillation		
	Conventional	
	Low Energy Use (heat integrated design)	
	Mechanical Vapor Recompression	

Table 11a. Energy Use for Ethanol Separation from Water: Anhydrous Ethanol from Dilute Solutions

Ethanol Concentration (% wt) Initial	Final	Process	Energy Use (kJ/l product ethanol)	Process Steam Use[a] (kg/l)	Status
8-10	99.9	Conventional two column distillation in typical cane alcohol distillery + azeotropic distillation w/benzene	9900-11,000	4.5-5.0	Com[b]
8-10	99.9	Heat integrated distillation in innovated cane alcohol distillery + azeotropic distillation w/benzene	6600-7700	3.0-3.5	Com[b]
6.4-10	99.9	Conventional two column distillation + azeotropic distillation with benzene	7630-9650	3.5-4.4	Com[c]
6.3-10	99.9	Conventional distillation with vapor re-use + azeotropic distillation with benzene	5000	2.3	Com[c]
10	99.9	Conventional distillation with vapor recompression + azeotropic distillation with benzene[e]	4400		Com[c]
10	99.9	Conventional distillation with vapor recompression + azeotropic distillation with benzene with vapor re-use[e]	4230		Com[c]
10	99.9	Conventional distillation + water adsorption in cornmeal	3340	1.5	Com[c]
10	99.9	Conventional distillation with vapor recompression + water adsorption in cornmeal[e]	2170		Com[c]
10	99.9	IHOSR distillation + extractive distillation with KAc salts	1700	0.8	Lab[c]
10	99.9	Extraction with CO2	2232-2791		Lab[d]
10	99.9	Solvent extraction	1005		Lab[d]
10	99.9	Vacuum distillation	10,330		Lab[d]

Table 11b. Energy Use for Ethanol Separation from Water: Hydrous (Azeotropic) Ethanol from Dilute Solutions

Ethanol Concentration (% wt) Initial	Final	Process	Energy Use (kJ/l product ethanol)	Process Steam Use[a] (kg/l)	Status
8-10	95	Conventional two column distillation in typical cane alcohol distillery	6600-7700	3.0-3.5	Com[b]
8-10	95	Heat integrated distillation in innovated cane alcohol distillery	3300-4400	1.5-2.0	Com[b]
6-10	95	Conventional two column distillation	4730-5850	2.1-2.7	Com[c]
6-10	95	Conventional distillation with vapor re-use	1950-3340	0.9-1.5	Com[c]
10	95	Conventional distillation with vapor recompression[e]	1610-1780		Com[c]
10	95	Three column distillation with vapor re-use	4730-5850	2.1-2.7	Com[c]
10	95	Four column distillation	8080	3.7	Com[c]
10	95	Three effect vacuum distillation	2010	0.9	Lab[d]

[a] The process steam is assumed to be saturated at 120°C, with enthalpy of vaporization of 2202 kJ/kg.

[b] G. Serra, Univerity of Sao Paulo, Campinas, Brazil, private communications, 1989.

[c] A. Serra, M. Poch and C. Sola, "A Survey of Separation Systems for Fermentation Ethanol Recovery," Process Biochemistry, pp.154-158, October 1987.

[d] G. Parkinson, "Batelle Maps Ways to Pare Ethanol Costs," Chemical Engineering, June 1, 1981.

[e] For vapor recompression, it is assumed that heat is converted into electricity at 33% efficiency.

Table 12. Electricity Production Potential with BIG/ISTIG in the Sugar Cane Industries of Developing Countries

	A	B	C	D	E = C/D
	Cane Production 1987[a]	Cane Production 2027[b]	Electricity Production: Potential from Cane in 2027[c]	Electricity Production: Actual from All Sources in 1987[d]	
	million tc/yr		TWh per year		
Africa					
South Africa	20.00	69.00	61.06	122.30[e]	0.50
Egypt	9.50	32.78	29.01	32.50	0.89
Mauritius	6.23	21.50	19.02	0.49	39.0
Sudan	5.00	17.25	15.27	1.06	14.5
Swaziland	4.00	13.80	12.21	-	-
Kenya	4.00	13.80	12.21	2.63	4.7
Zimbabwe	3.80	13.11	11.60	7.01	1.7
Reunion	2.11	7.29	6.45	-	-
Madagascar	1.80	6.21	5.50	0.50	10.9
Ivory Coast	1.75	6.04	5.34	2.20	2.4
Ethiopia	1.65	5.69	5.04	0.81	6.2
Malawi	1.60	5.52	4.89	0.58	8.5
Nigeria	1.55	5.35	4.73	9.91	0.48
Cameroon	1.29	4.45	3.94	2.39	1.7
Zambia	1.25	4.31	3.82	8.48	0.45
Zaire	1.09	3.75	3.32	5.30	0.63
Tanzania	1.08	3.71	3.28	0.87	3.8
Morocco	0.80	2.76	2.44	8.32	0.29
Senegal	0.70	2.42	2.14	0.75	2.8
Mozambique	0.67	2.31	2.05	0.50	4.1
Uganda	0.60	2.07	1.83	0.66	2.8
Congo	0.51	1.76	1.56	0.24	6.6
Somalia	0.37	1.28	1.13	0.26	4.4
Burkina Faso	0.33	1.14	1.01	0.13	7.8
Angola	0.32	1.10	0.98	0.81[f]	1.2
Chad	0.29	1.00	0.89	-	-
Mali	0.22	0.76	0.67	0.20	3.3
Guinea	0.20	0.69	0.61	0.50	1.2
Liberia	0.16	0.54	0.47	0.83	0.57
Gabon	0.14	0.48	0.43	0.88	0.49
Niger	0.11	0.38	0.34	0.16	2.1
Ghana	0.11	0.38	0.34	4.71	0.07
Sierra Leone	0.07	0.24	0.21	0.20	1.1
Rwanda	0.032	0.11	0.097	0.17	0.56
SUBTOTALS	73.3	253.0	223.9	216.4	1.03
Oceania					
Fiji	3.49	12.05	10.67	0.43	25.0
Papua N. Guinea	0.23	0.80	0.71	1.80	0.39
SUBTOTALS	3.7	12.9	11.4	2.2	5.1

Table 12, cont.

	A	B	C	D	E = C/D
	Cane Production 1987[a]	Cane Production 2027[b]	Electricity Production Potential from Cane in 2027[c]	Electricity Production Actual from All Sources in 1987[d]	
	million tc/yr		TWh per year		
Central America					
Cuba	65.60	226.32	200.29	13.20[e]	15.0
Mexico	42.56	146.83	129.95	104.79	1.2
Dominican Republic	8.60	29.67	26.26	5.00	5.3
Guatemala	6.90	23.80	21.07	2.08	10.2
El Salvador	3.18	10.97	9.71	1.89	5.1
Honduras	3.00	10.35	9.16	1.81	5.1
Costa Rica	3.00	10.35	9.16	3.13	2.9
Haiti	3.00	10.35	9.16	0.45	20.4
Nicaragua	2.58	8.88	7.86	1.24	6.3
Jamaica	2.01	6.93	6.14	2.39	2.6
Panama	1.60	5.52	4.89	2.85	1.7
Trinidad & Tobago	1.24	4.26	3.77	3.30[e]	1.1
Belize	0.86	2.98	2.64	0.075	35.0
Guadaloupe	0.75	2.57	2.28	-	-
Barbados	0.73	2.52	2.23	0.43	5.2
St. Kitts Nev.	0.25	0.86	0.76	-	-
Martinique	0.25	0.86	0.76	-	-
Bahamas	0.24	0.83	0.73	-	-
SUBTOTALS	146.4	504.9	446.8	142.6	3.1
South America					
Brazil	273.86	944.79	836.14	202.29	4.1
Colombia	24.97	86.15	76.22	35.37	2.2
Argentina	14.00	48.30	42.75	52.17	0.82
Peru	5.95	20.53	18.17	14.20	1.3
Venezuela	7.00	24.15	21.37	50.21	0.43
Ecuador	5.20	17.94	15.88	5.67	2.8
Guyana	3.30	11.38	10.08	-	-
Paraguay	3.19	11.00	9.73	2.83	3.5
Bolivia	2.73	9.42	8.34	1.52	5.5
Uruguay	0.65	2.24	1.99	4.53	0.44
Suriname	0.11	0.38	0.34	-	-
SUBTOTALS	341.0	1176.3	1041.0	368.8	2.8

Table 12, cont.

	A	B	C	D	E = C/D
	Cane Production		Electricity Production		
	1987[a]	2027[b]	Potential from Cane in 2027[c]	Actual from All Sources in 1987[d]	
	million tc/yr		TWh per year		
Asia					
India	182.48	629.55	557.15	217.50	2.6
China	52.55	181.30	160.45	497.30	0.32
Pakistan	31.70	109.37	96.80	28.40	3.4
Thailand	24.45	84.35	74.65	29.99	2.5
Indonesia	21.76	75.09	66.45	34.81	1.9
Philippines	13.33	45.97	40.68	23.85	1.7
Bangaldesh	6.90	23.79	21.06	5.90	3.6
Vietnam	6.60	22.77	20.15	5.20[e]	3.9
Burma	3.28	11.32	10.02	2.28	4.4
Iran	1.15	3.97	3.51	36.80[e]	0.10
Malaysia	1.15	3.97	3.51	16.22	0.22
Sri Lanka	0.80	2.76	2.44	2.71	0.90
Nepal	0.62	2.13	1.88	0.54	3.5
Kampuchea	0.21	0.71	0.63	-	-
Laos	0.11	0.36	0.32	0.88	0.37
SUBTOTALS	347.1	1197.4	1059.7	902.4	1.2
GRAND TOTALS	911.5	3144.4	2782.8	1632.4	1.7

a Food and Agriculture Organization, FAO Production Yearbook, FAO Statistical Series No. 82, vol. 21, 1987.

b Assuming sugar cane grows at a rate of 3.1%/yr.

c For sugar factories or alcohol distilleries operated 133 days/yr, with 286 kWh of electricity produced from bagasse/tc during the milling season plus 599 kWh produced from barbojo/tc during the off-season, with BIG/ISTIG units.

d Except where otherwise indicated, from J.R. Escay, IENED, "Summary Data Sheets of 1987 Power and Commercial Energy Statistics for 100 Developing Countries," Industry and Energy Department Working Paper, Energy Series Paper No. 23, World Bank, March 1990.

e For 1986, from Bureau of the Census, US Dept. of Commerce, Statistical Abstract of the United States 1989, 109th Edtion, US Government Printing Office, Washington, DC, January 1989.

f Public electricity production in 1989. From E.A. Moore (IENED) and G. Smith, "Capital Expenditures for Electric Power in the Developing Countries inthe 1990s," Industry and Energy Department Working Paper, Energy Series Paper No. 21, World Bank, February 1990.

Table 13a. Net Potential CO2 Emissions Reduction for Alternative Energy Systems at Sugar Factories and Alcohol Distilleries (kg C/tc)

	Sugar Factories				
	Conventional Power System	CEST	BIG/STIG	BIG/ISTIG	BIG/ISTIG w/Shortened Milling Season
Gross CO2 Reduction					
1. If Extra Cogenerated Electricity Displaces Coal-Based Electricity[a]	-	76.2	169.4	184.5	226.4
CO2 Penalties					
1. Barbojo Recovery[b]	-	1.4	1.6	1.4	1.9
2. Power Plant Construction[c]	-	0.5	1.1	1.1	1.3
3. Power Plant O&M[d]	-	1.3	3.0	3.0	3.6
4. Subtotals	-	3.2	5.7	5.5	6.8
Net CO2 Reduction	-	73.0	163.7	179.0	219.6

	Alcohol Distilleries				
	Conventional Power System	CEST	BIG/STIG	BIG/ISTIG	BIG/ISTIG w/Shortened Milling Season
Gross CO2 Reduction					
1. If Extra Cogenerated Electricity Displaces Coal-Based Electricity[a]	-	76.2	169.4	184.5	226.4
2. If EthOH Displaces Oil[e]	45.3	45.3	45.3	45.3	45.3
3. If CH4 Displaces Oil[f]	7.3	7.3	7.3	7.3	7.3
4. Subtotals	52.6	128.8	222.0	237.1	279.0
CO2 Penalties					
1. Cane Production, Harvesting, and Transport[g]	6.1	7.5	7.7	7.5	8.0
2. Distillery Manufacture[h]	1.3	1.3	1.3	1.3	1.3
3. Distillery O&M[h]	2.2	2.2	2.2	2.2	2.2
4. Power Plant Construction[c]	-	0.5	1.1	1.1	1.3
5. Power Plant O&M[d]	-	1.3	3.0	3.0	3.6
6. Subtotals	9.6	12.8	15.3	15.1	16.4
Net CO2 Reduction	43.0	116.1	206.7	222.0	262.6

Table 13b. Potential CO2 Emissions Reduction in Developing Countries in 2027 for Alternative Energy Systems Installed at Sugar Factories and Alcohol Distilleries (megatonnes C/yr)

	Conventional Power System	CEST	BIG/STIG	BIG/ISTIG	BIG/ISTIG w/Shortened Milling Season
At Sugar Factories[i]	-	125.0	284.9	306.1	375.7
At Alcohol Distilleries[i]	61.5	166.0	299.6	317.5	375.7
Totals	61.5	291.0	584.5	623.6	751.4

Notes for Table 13

[a] For a 160-day milling season, the electricity generated in excess of onsite needs in the milling season (off-season) is 92 kWh/tc (206 kWh/tc) for CEST, 242 kWh/tc (420 kWh/tc) for BIG/STIG, and 286 kWh/tc (435 kWh/tc) for BIG/ISTIG. For a 133-day milling season, offseason production is 599 kWh/tc for BIG/ISTIG. It is assumed that this electricity displaces electricity that would otherwise be produced at coal power plants @ 10.4 MJ/kWh and that 24.6 kg C is released (as CO2) per GJ of coal burned.

[b] When barbojo is recovered for offseason fuel, it is assumed that the agricultural fuel use increases in proportion to the mass of the recovered barbojo. Assuming that the total amount of barbojo is 660 kg per tonne of cane, the energy penalty for barbojo recovery is FB*0.66*(0.18 GJ/tc) (Table 14), where FB is the fraction of barbojo recovered. For a 160-day milling season, FB = 0.58, 0.68, and 0.58, for CEST, BIG/STIG, and BIG/ISTIG, respectively. For a 133-day growing season, FB = 0.80 for BIG/ISTIG. Assuming the fuel used to recover barbojo is oil, 19.9 kg of carbon would be released (as CO2) per GJ of oil burned.

[c] The energy required to build a power plant is assumed to be 14.8 GJ/kWe (A.M. Perry, W.D. Devine, D.B. Reister, "The Energy Cost of Energy--Guidelines for Net Energy Analysis of Energy Supply Systems," Institute for Energy Analysis, Oak Ridge Associated Universities, August 1977), or 0.493 GJ/yr/kWe for a 30-year plant life. For a 160-day milling season, the extra electrical generating capacity needed for cogeneration equipment is 0.039 kW, 0.088 kW, and 0.092 kW per tc/yr of cane processing capacity, for CEST, BIG/STIG, and BIG/ISTIG, respectively. For a 133-day milling season, the needed extra electrical capacity is 0.110 kW per tc/yr for BIG/ISTIG. It is assumed that the fuel required to build power plants is coal.

[d] As for the Brazilian distillery analysis (Table 14) it is assumed that the maintenance and operation fossil energy penalties are 5.0% and 3.9% of the energy required to construct the power plant, respectively. Thus the O&M penalty is 30*0.089 = 2.67 times the construction energy penalty.

[e] It is assumed that 70 liters of fuel alcohol is produced per tc and that 1 liter of alcohol is equivalent as a motor fuel to 0.84 liters of gasoline. Thus, taking into account 10% refinery losses in producing gasoline, the produced alcohol would displace 2.28 GJ of crude oil per tc.

[f] Assuming 0.33 GJ/tc of methane is produced via anaerobic digestion of stillage and used to displace gasoline, or 0.37 GJ of crude oil/tc.

[g] The agricultural energy (assumed to be oil) required for cane production for conventional distilleries is from Table 14. The incremental agricultural energy required for barbojo recovery is estimated in note b.

[h] Energy (assumed to be coal) for distillery manufacture is from Table 14.

[i] Assuming 1710 (1430) million tonnes of sugar cane are associated with sugar (alcohol) production in developing countries in 2027.

Table 14. Fossil Energy Requirements Associated with Alcohol Production from Sugar Cane at Conventional Plants in Brazil[a]

	GJ/ha/yr	MJ/tc[b]
Agricultural Energy Requirements		
Manufacture of tractors, trucks, other agricultural equipment	1.68	32.3
Fuel for tractors, harvestors, trucks, etc.	9.37	180.2
N-fertilizer	2.88	55.4
P-fertilizer	0.37	7.1
K-fertilizer	0.40	7.7
Lime	0.15	2.9
Seeds	0.79	15.2
Insecticides	0.01	0.2
Herbicides	0.23	4.4
Subtotal	15.88	305.4
Distillery Energy Requirements		
Manufacture of Distillery[c]		51.5
Distillery Operation[d]		40.2
Distillery Maintenance[e]		51.5
Subtotal		143.2
Total Energy Requirements for Alcohol Production		448.6

a Source: J.R. Moreira, V.R. Vanin, and J. Goldemberg (Institute of Physics, University of Sao Paulo, Sao Paulo, Brazil), "Energy Balance for the Production of Ethyl and Methyl Alcohol," presented at the Workshop on Fermentation Alcohol for Use as Fuel and Chemical Feedstock in Developing Countries, Vienna, Austria, March 26-30, 1979.

b The average harvested yield of sugar cane is 52 tonnes/ha/yr.

c The energy required to build a 120,000 l/day distillery is estimated to be 254.4 TJ. Assuming the distillery operates 160 days per year @ 90% availability and lasts for 20 years, the manufacturing energy amounts to 736.1 kJ/liter of produced alcohol or 51.5 MJ/tc, assuming 70 liters of alcohol are produced per tc.

d Estimated to be 3.9% of the energy of distillery manufacture per year.

e Estimated to be 5.0% of the energy of distillery manufacture per year.

Table 15. Investment Requirements for the Power Sector in Developing Countries, as Estimated by the World Energy Conference (WEC)[a]

	1980	2000L[b]	2000H[b]
Unit Cost for New Generating Capacity (1986 $/kW)			
Hydroelectric	2660	3260	3990
Nuclear	2000	2460	3000
Fossil Fuel, Thermal	1000	1200	1460
Average Unit Capital Cost (1986$/kW)			
Generation	1640	2010	2410
T & D	790	1650	2410
Total Investment Requirements (billion 1986 $)			
Generation	28	79	185
Transmission & Distribution	15	65	185
Total	43	144	370
(as % of GDP)	(1.5)	(2.6)	(5.5)

[a] Source: H.K. Schneider and W. Schulz, Investment Requirements of the World Energy Industries 1980-2000, report prepared for the WEC Study on Long-Term Investment Requirements, Needs, Constraints, and Proposals, World Energy Conference, London, September, 1987.

[b] "L" ("H") refers to the WEC low (high) growth scenario, for which GDP grows at an average rate of 3.5%/yr (4.5%/yr), 1980-2000.

Table 16a. Present/Future[a] Distribution of Fossil Fuel CO_2 Emissions (GT/yr)

	1985	2025 RCW	2025 SCW	2050 RCW	2050 SCW
Industrialized Countries					
Market	2.6	2.8	2.4	3.2	2.3
Centrally Planned	1.5	2.1	2.1	3.0	2.0
Subtotal	4.1	4.9	4.5	6.2	4.3
Developing Countries					
Market	0.8	3.4	1.9	5.6	2.3
Centrally Planned	0.6	2.0	1.0	3.5	1.3
Subtotal	1.4	5.4	2.9	9.1	3.6
Global	5.5	10.3	7.4	15.3	7.9

Table 16b. Present/Future[a] Distribution of Population (millions)

	1985	2025 RCW	2025 SCW	2050 RCW	2050 SCW
Industrialized Countries					
Market	813	938	943	928	923
Centrally Planned	416	500	514	521	533
Subtotal	1229	1438	1457	1449	1456
Developing Countries					
Market	2500	5024	5522	6212	7543
Centrally Planned	1140	1728	1672	1866	1805
Subtotal	3640	6752	7194	8078	9348
Global	4869	8190	8651	9527	10804

Table 16c. Present/Future[a] Distribution of Per Capita Fossil Fuel CO_2 Emissions (tonnes/yr)

	1985	2025 RCW	2025 SCW	2050 RCW	2050 SCW
Industrialized Countries					
Market	3.20	2.99	2.55	3.45	2.49
Centrally Planned	3.62	4.20	4.09	5.76	3.75
Subtotal	3.34	3.41	3.09	4.28	2.95
Developing Countries					
Market	0.32	0.68	0.34	0.90	0.30
Centrally Planned	0.53	1.16	0.60	1.88	0.72
Subtotal	0.39	0.80	0.40	1.13	0.39
Global	1.13	1.26	0.86	1.61	0.73

[a] The projections were made by the US Environmental Protection Agency for its Rapidly Changing World (RCW) Scenario and its Slowly Changing World (SCW) Scenario in its 1989 study on policy options for coping with global warming [US Environmental Protection Agency, "Policy Options for Stabilizing the Global Climate," February 1989 (draft)].

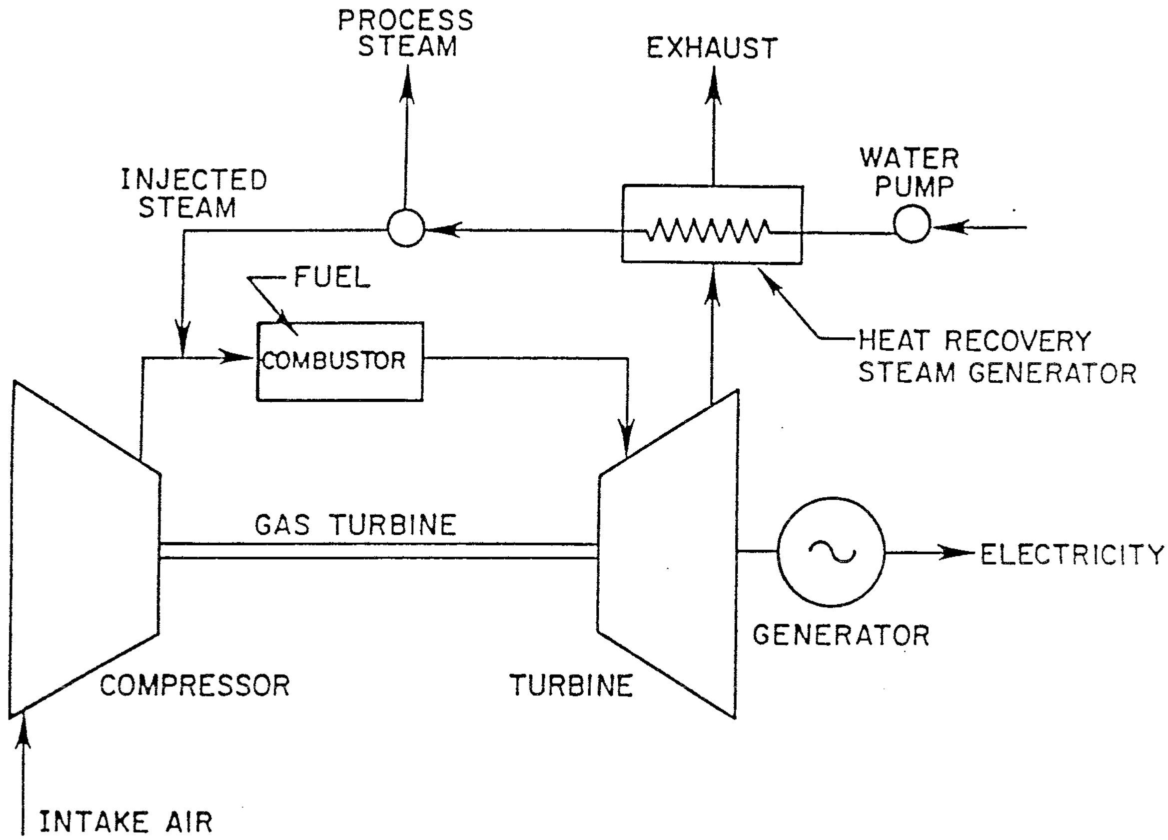


Figure 1a.

Steam-Injected Gas Turbine (STIG)

Fuel burns in air pressurized by a compressor. The combustion products drive a turbine. The turbine exhaust gases are used to raise steam in a heat recovery steam generator (HRSG). The steam not needed for process is injected into the combustor and at points further down the flow path for increased power output and electrical efficiency.

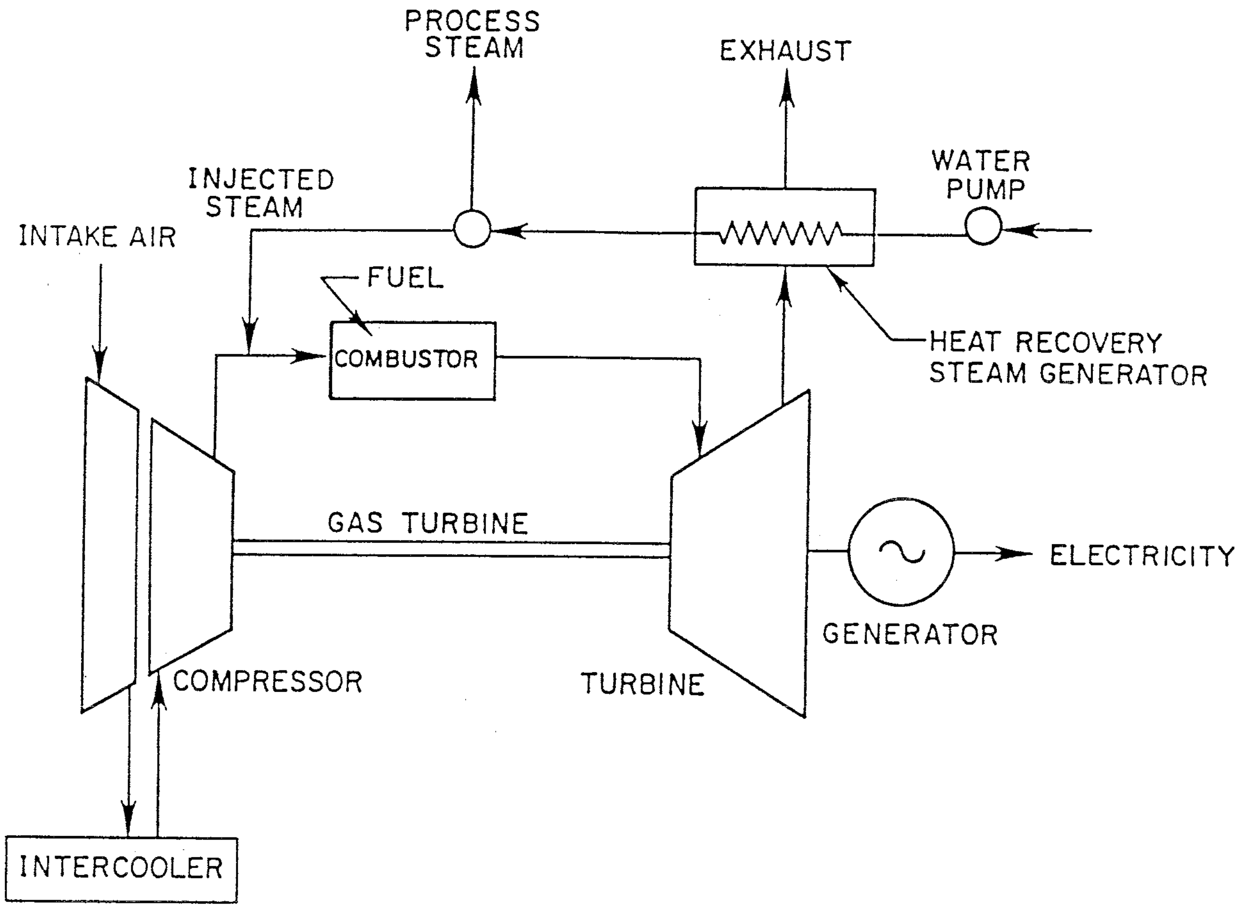


Figure 1b.

Intercooled Steam-Injected Gas Turbine (ISTIG)

Like STIG except that an intercooler between compressor stages reduces compressor work requirements and allows for operation at much higher turbine inlet temperature because of improved air cooling of turbine blades.

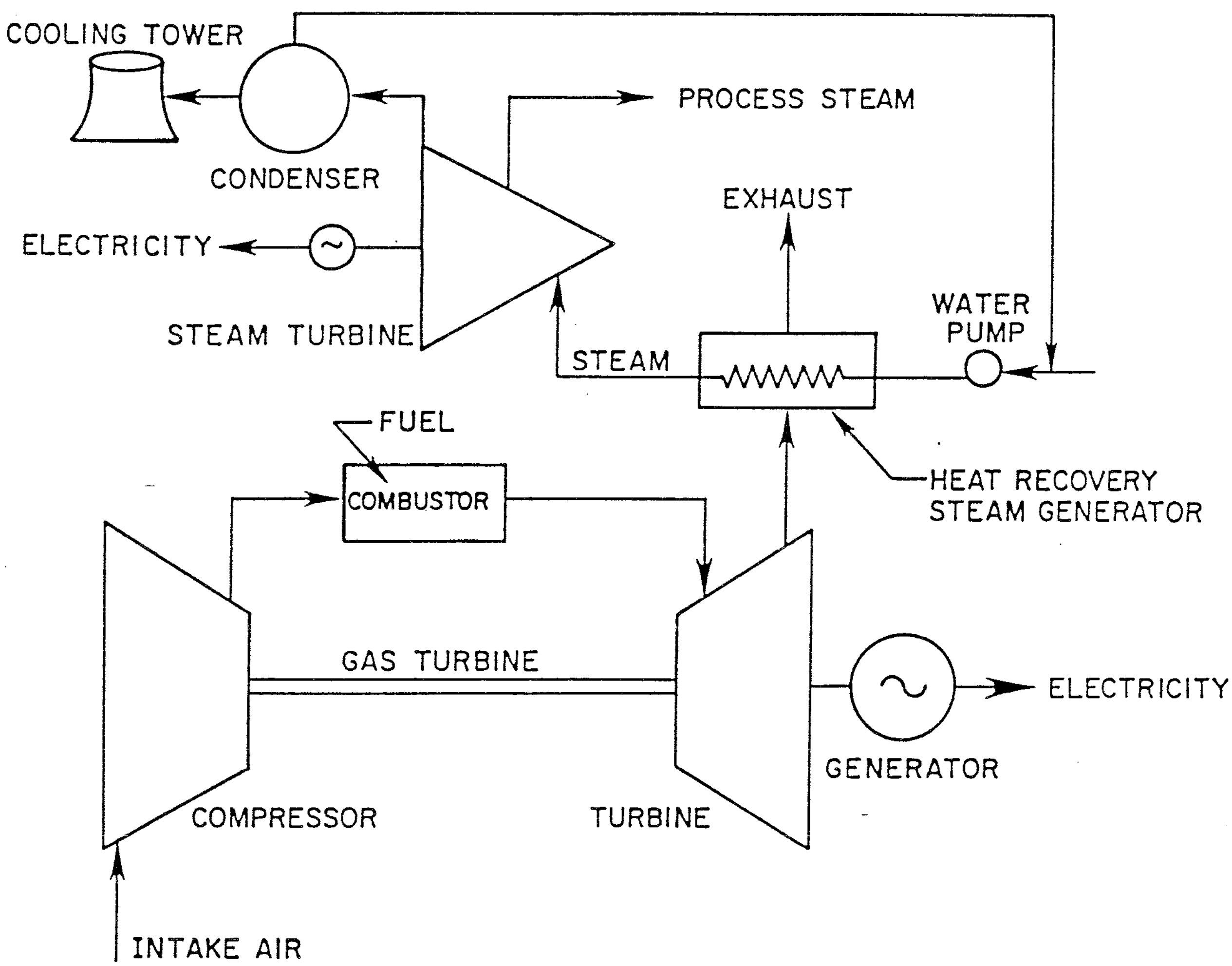


Figure 1c.

Combined Cycle

Steam from the HRSG is used to produce extra power in a condensing steam turbine, from which some steam might be bled for process applications.

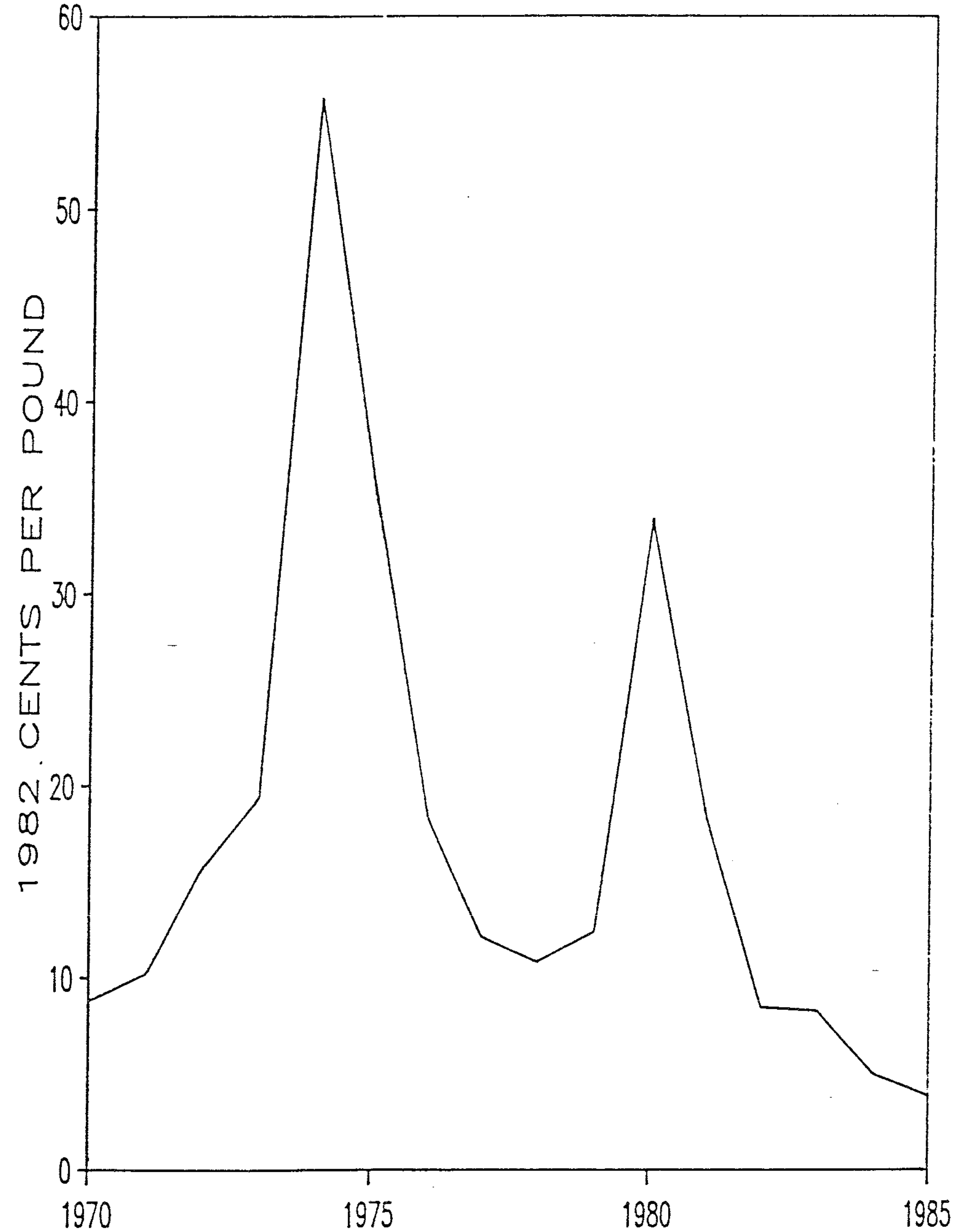


Figure 2.

The World Market Price for Sugar, 1970-1985

Current dollar prices (from International Sugar Organization, Sugar Yearbook, London, annual) have been converted to 1982 dollars using the GNP deflator.

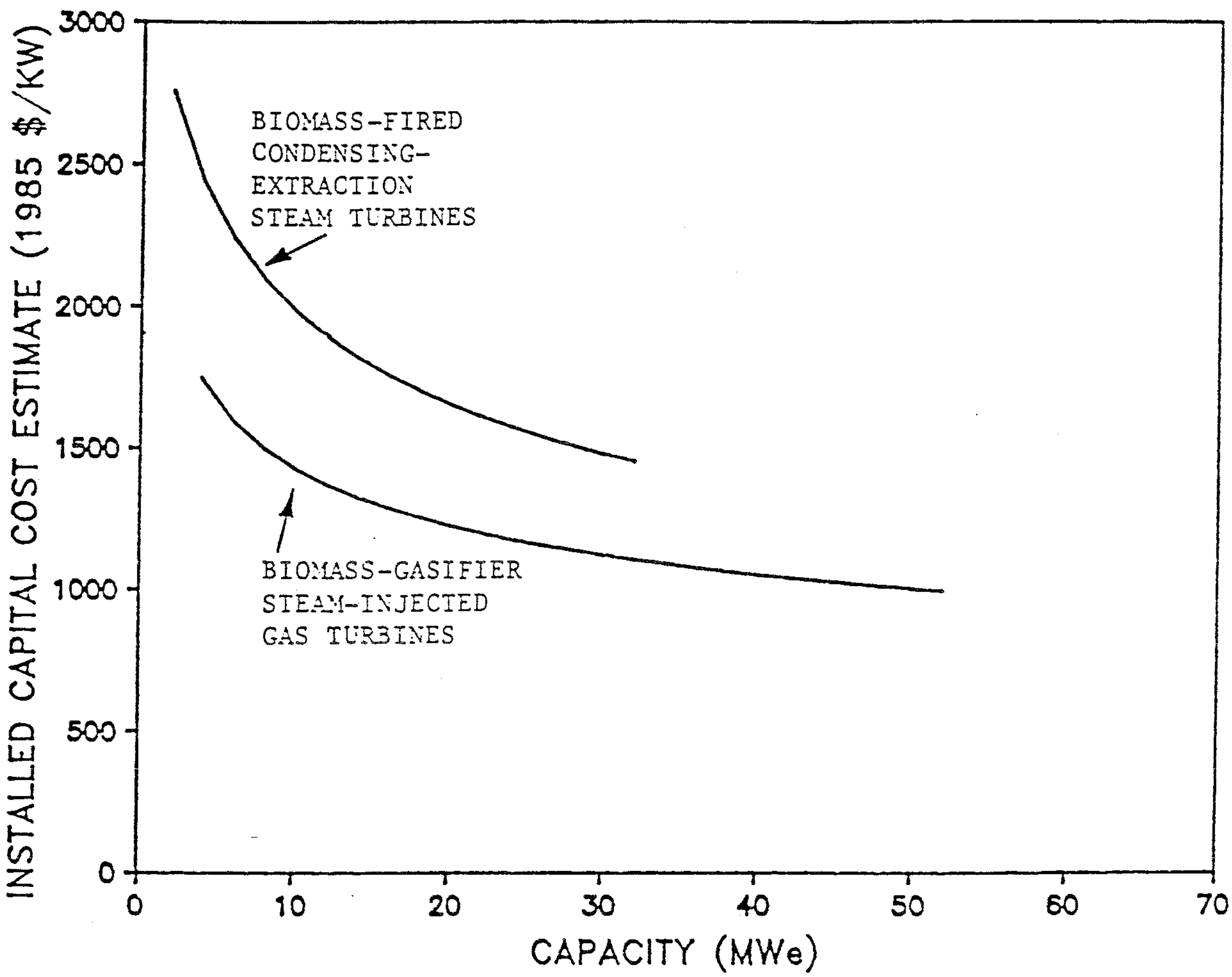
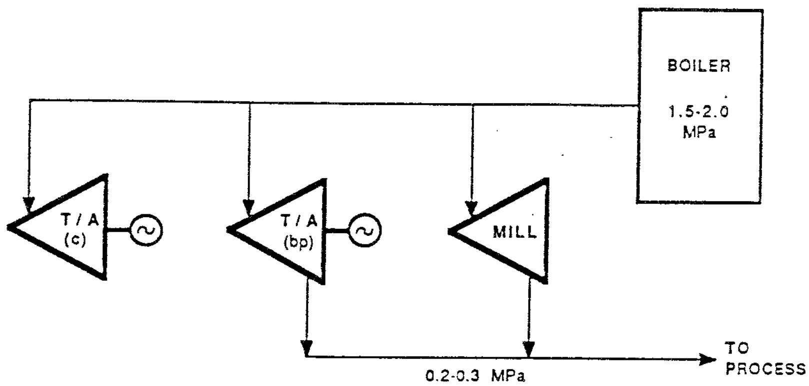


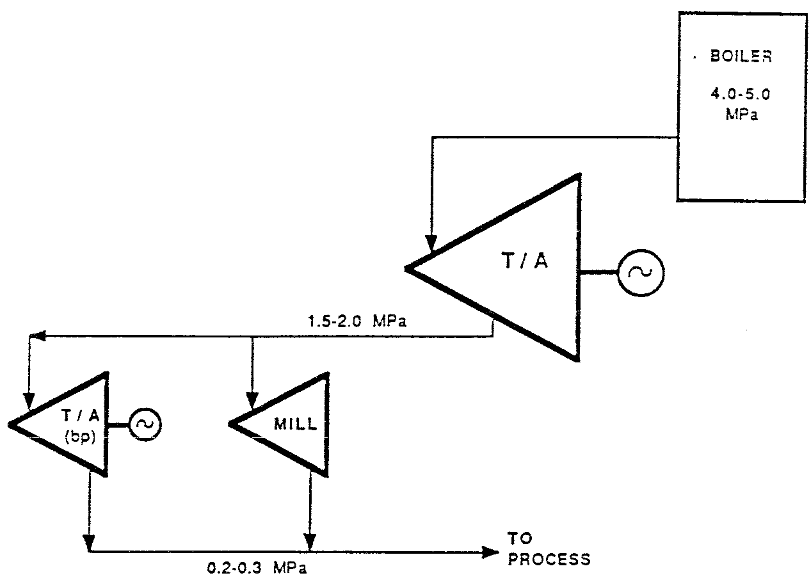
Figure 3.

Estimated Unit Installed Capital Costs for Biomass-Fired Condensing/Extraction Steam Turbine (CEST) and Biomass-Integrated Gasifier/Steam-Injected Gas Turbine (BIG/STIG) Units for Cogeneration Applications

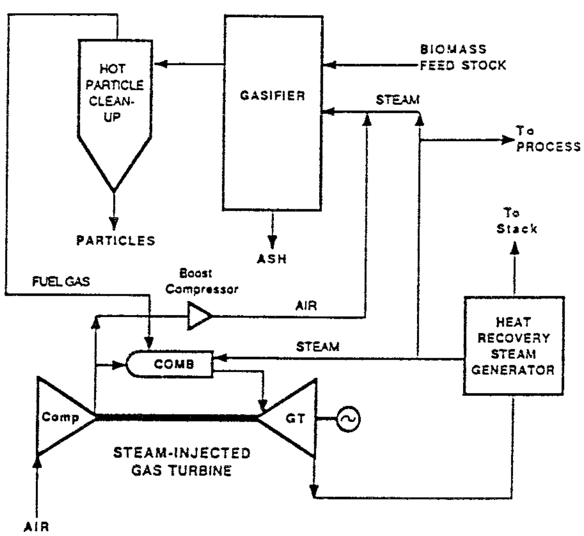
Source: E.D. Larson and R.H. Williams, "Biomass Gasifier Steam-Injected Gas Turbine Cogeneration," Journal of Engineering for Gas Turbines and Power, vol. 112, pp. 157-163, April 1990.



a) Conventional steam turbine typical of today's factories



b) High-pressure, condensing/ extraction steam turbine (CEST)



c) Biomass-integrated gasifier/ steam-injected gas turbine (BIG/STIG)

Figure 4.

Alternative Cogeneration Systems for a Cane Sugar Factory or Alcohol Distillery

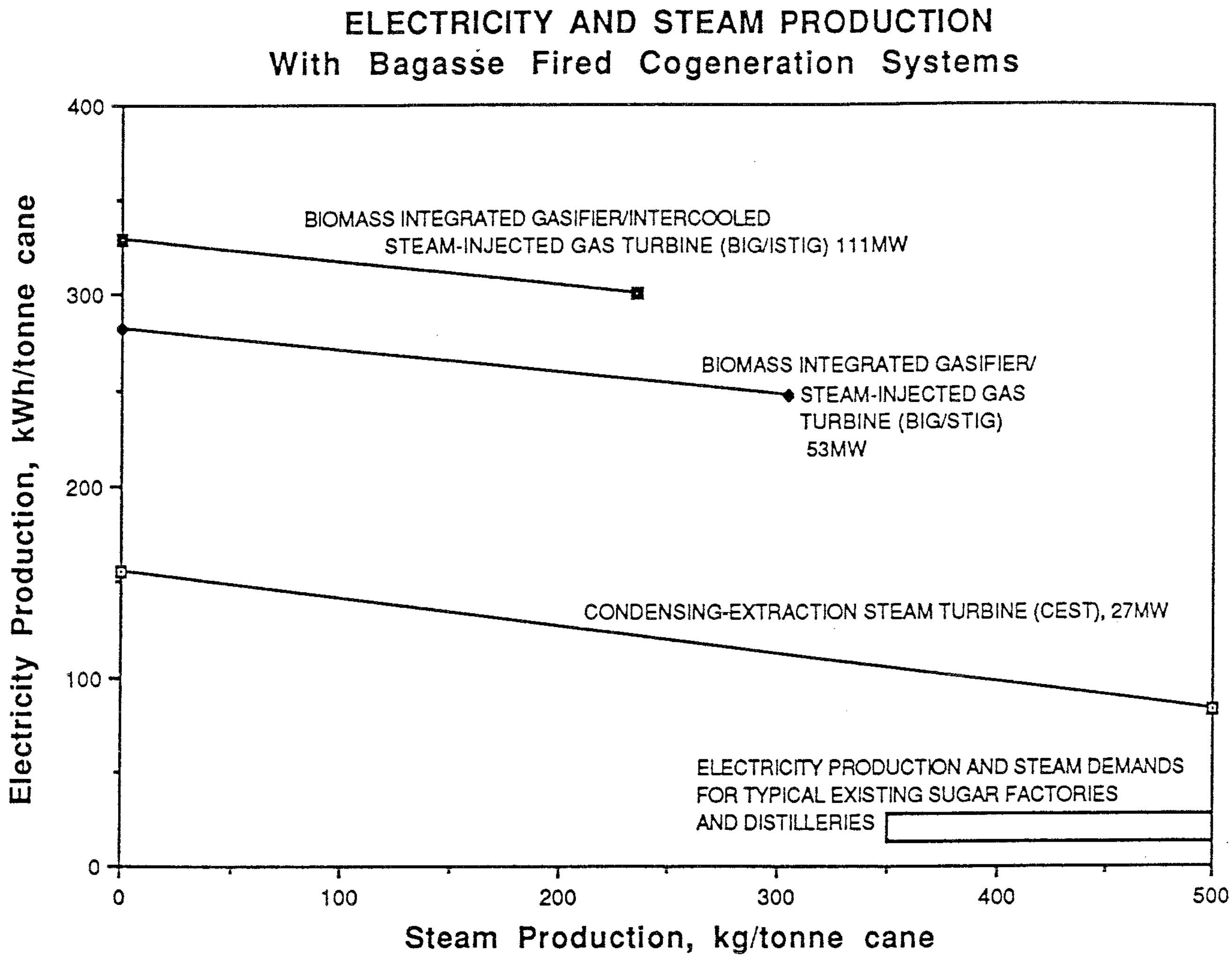


Figure 5.

Electricity and Steam Production Estimates for Alternative Bagasse-Fired Cogeneration Systems

Performance estimates are shown for the condensing-extraction steam turbine (CEST), the biomass integrated gasifier/steam-injected gas turbine (BIG/STIG), and the biomass integrated gasifier/intercooled steam-injected gas turbine (BIG/ISTIG) operating at sugar factories or alcohol distilleries during the milling season. Steam production is given in kilograms of steam produced per tonne of cane milled (kg/tc) and electricity production is in kilowatt hours per tonne of cane (kWh/tc). Also shown are the steam and electricity production from a typical sugar factory or distillery cogeneration system today.

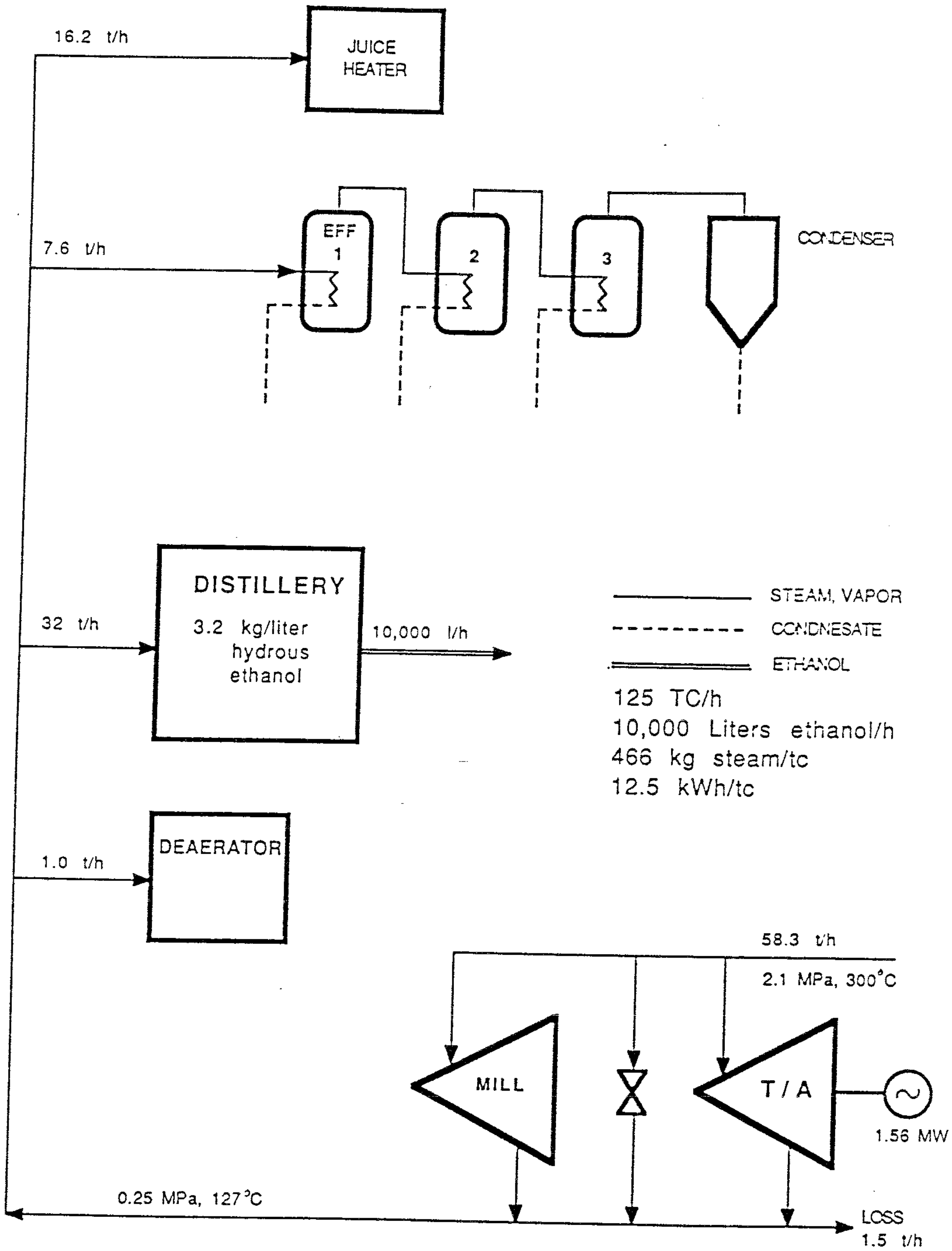


Figure 6a.

Factory Flow Diagram Showing Steam and Material Flows in a Typical Brazilian Autonomous Distillery

This distillery mills 125 tonnes of cane and produces 10,000 liters of hydrous ethanol per hour. A conventional distillation system is used, requiring 3.2 liters of steam per liter of hydrous ethanol. The estimated factory steam demand is 466 kg/tc. The electricity demand is 12.5 kWh/tc.

Source: J.L. Oliverio, J.D. Neto, and J.F.P. de Miranda, "Energy Optimization and Electricity Production in Sugar Mills and Alcohol Distilleries," Proceedings of the 20th Congress of the International Society of Sugar Cane Technologists, Sao Paulo, Brazil, October 12-21, 1989.

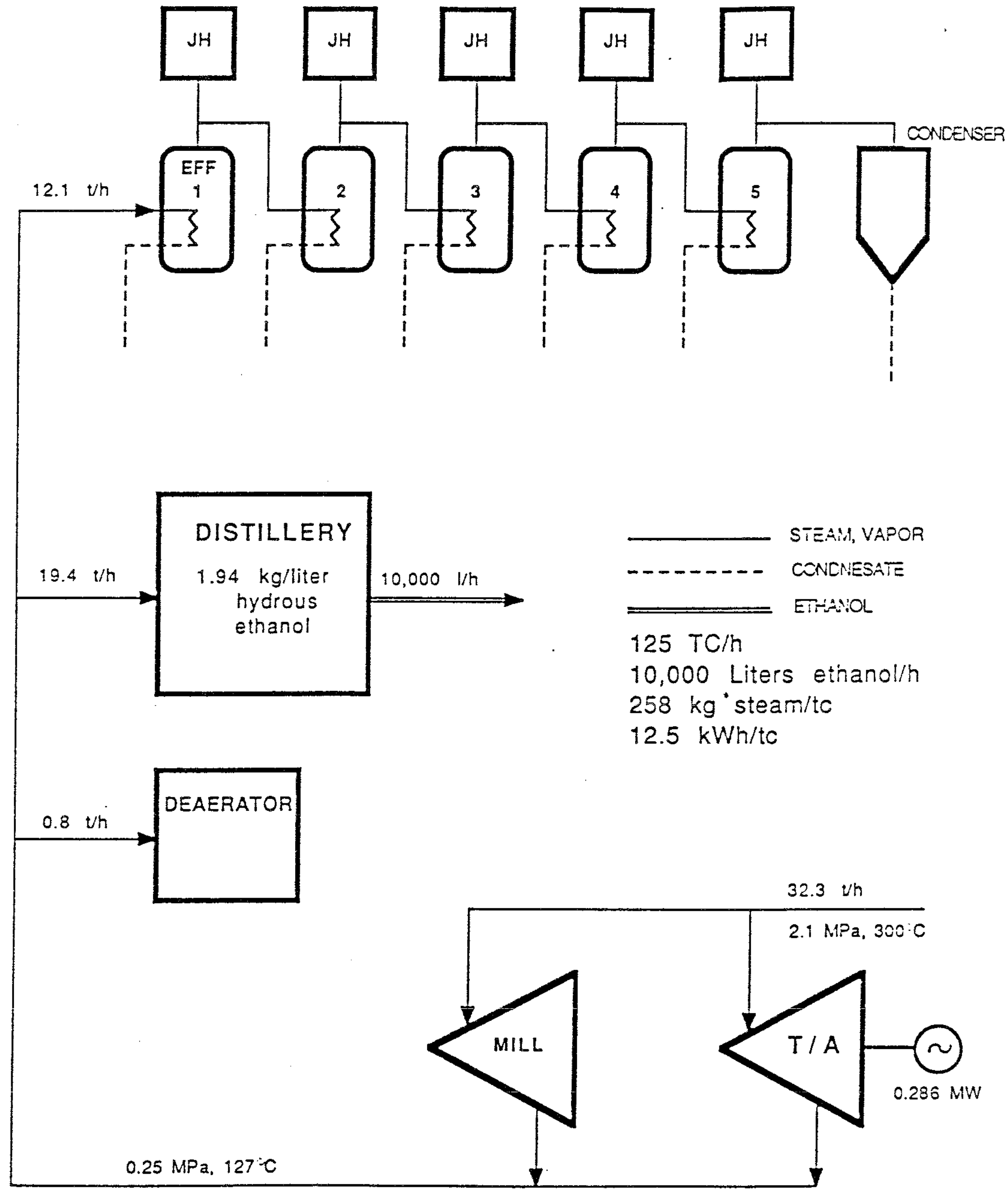


Figure 6b.

Factory Flow Diagram Showing Steam and Material Flows in a Steam-Conserving Brazilian Autonomous Distillery

This distillery mills 125 tonnes of cane and produces 10,000 liters of hydrous ethanol per hour. Steam use is reduced by using vapors bled from the evaporator for juice heating and a more energy-efficient distillation system with heat integration, requiring 1.9 liters of steam per liter of hydrous ethanol. The estimated factory steam demand is 258 kg/tc. The electricity demand is 12.5 kWh/tc.

Source: J.L. Oliverio, J.D. Neto, and J.F.P. de Miranda, "Energy Optimization and Electricity Production in Sugar Mills and Alcohol Distilleries," Proceedings 20th Congress of the International Society of Sugar Cane Technologists, Sao Paulo, Brazil, October 12-21, 1989.

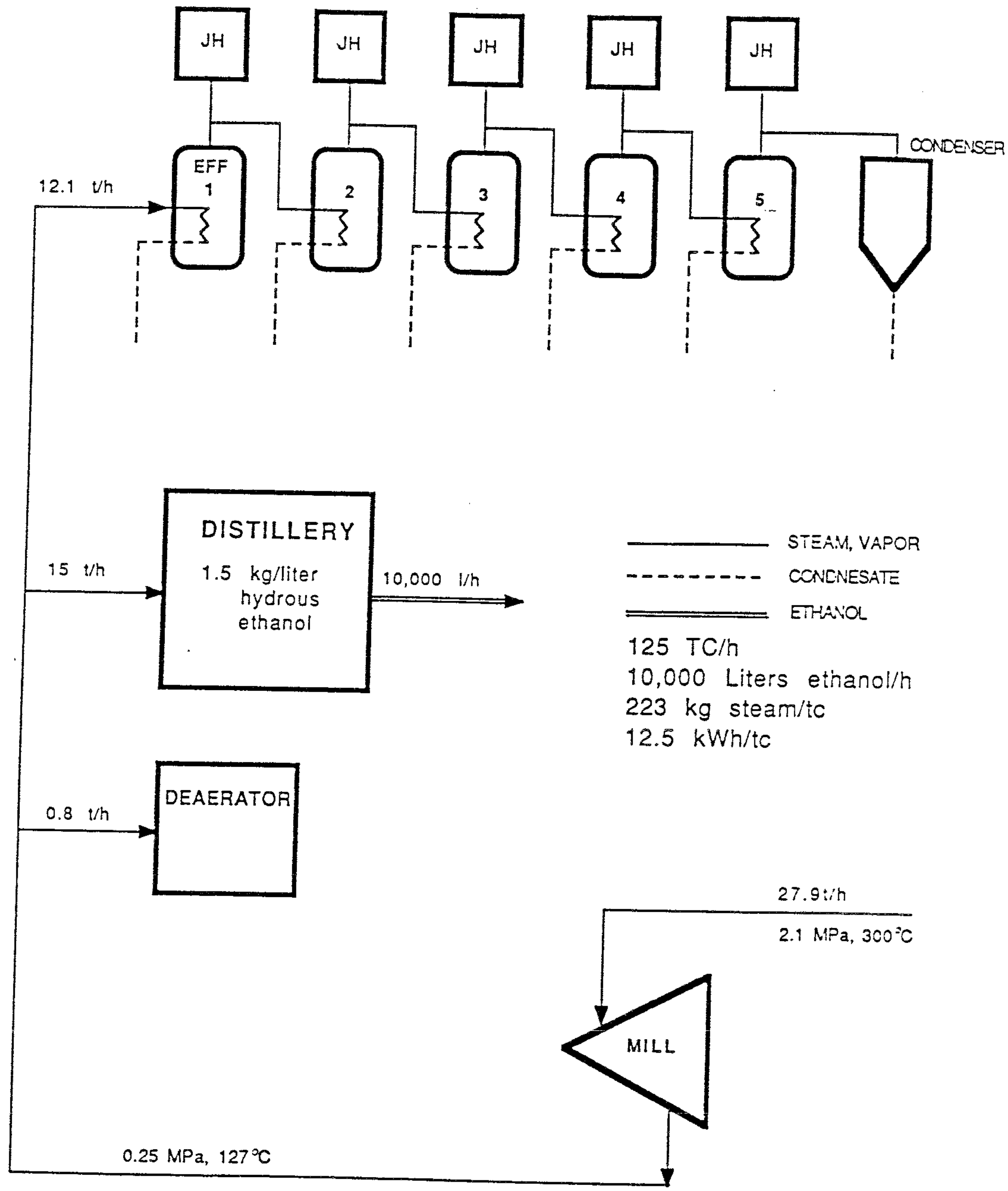


Figure 6c.

Factory Flow Diagram Showing Steam and Material Flows in a Steam-Conserving Brazilian Autonomous Distillery

This distillery mills 125 tonnes of cane and produces 10,000 liters of hydrous ethanol per hour. Steam use is reduced by using vapors bled from the evaporator for juice heating and a more energy-efficient distillation system with heat integration, requiring 1.5 liters of steam per liter of hydrous ethanol. The estimated factory steam demand is 225 kg/tc. The electricity demand is 12.5 kWh/tc.

Sources: J.L. Oliverio, J.D. Neto, and J.F.P. de Miranda, "Energy Optimization and Electricity Production in Sugar Mills and Alcohol Distilleries," Proceedings 20th Congress of the International Society of Sugar Cane Technologists, Sao Paulo, Brazil, October 12-21, 1989; J. Goldemberg, J.R. Moreira, P.U.M. Dos Santos, and G.E. Serra, "Ethanol Fuel: A Use of Biomass Energy in Brazil," Ambio, Vol. 14, No. 4-5, 1985; G. Serra and J.R. Moreira, University of Sao Paulo, Brazil, private communications, 1989.

AUTONOMOUS DISTILLERY SETUP

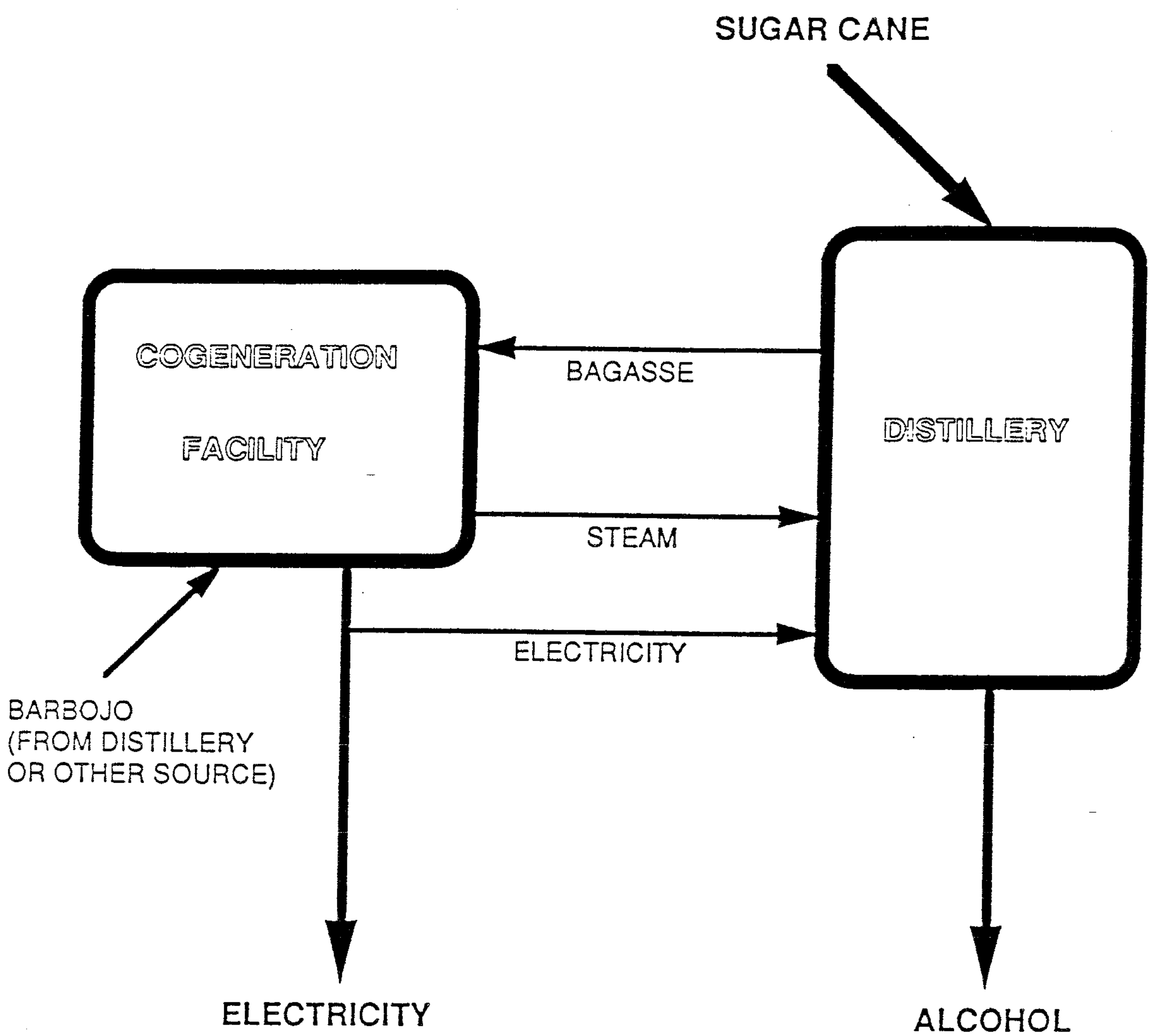


Figure 7.

Material and Energy Flows for an Autonomous Distillery and Cogeneration Facility

It is assumed that during the milling season the cogenerator buys bagasse fuel from the distiller and sells him steam and electricity. It is assumed that during the off-season, the cogenerator buys barbojo as fuel--either from the distiller (if the distiller owns the cane fields) or from independent cane producers. (Note that if it is not feasible or practical to recover the barbojo, fuelwood, oil, or another alternative fuel could instead be used in the off-season.)

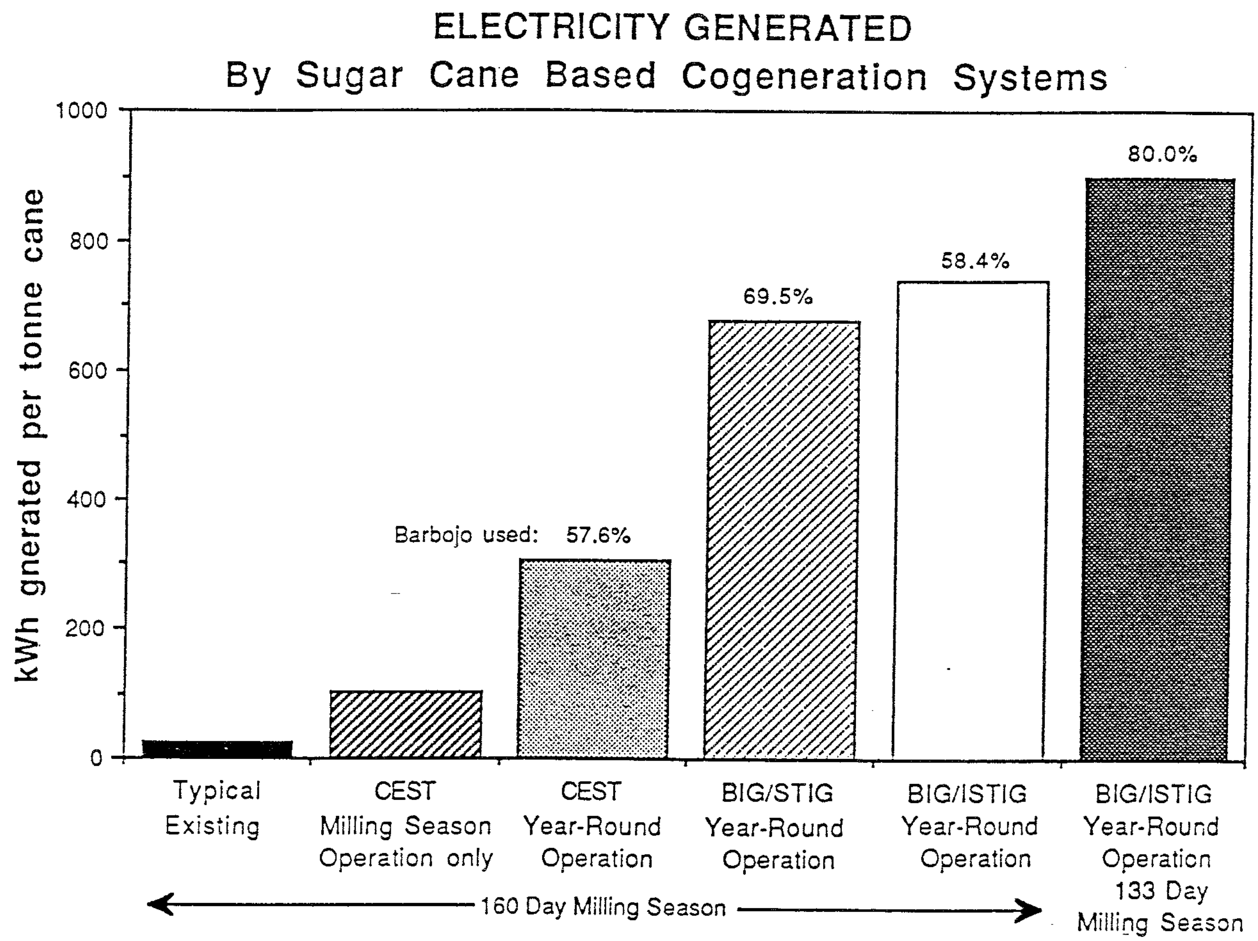


Figure 8.

The Potential for Cogeneration Using Sugar Cane Residues

The first bar is for a typical existing situation at a sugar factory or alcohol distillery during the the milling season. The next bar is for a CEST system operating during the milling season at a factory where steam-saving retrofits have been made. The next three bars are for year-round operation for a plant at which steam-saving retrofits have been made and where the milling season is 160 days: the third, fourth, and fifth bars are for CEST, BIG/STIG, and BIG/ISTIG systems, respectively. The sixth bar is for a BIG/ISTIG unit operated at a steam-efficient plant operated with a 133-day milling season. The number at the tops of the four bars to the right is the percentage of the barbojo used for power generation during the off-season.

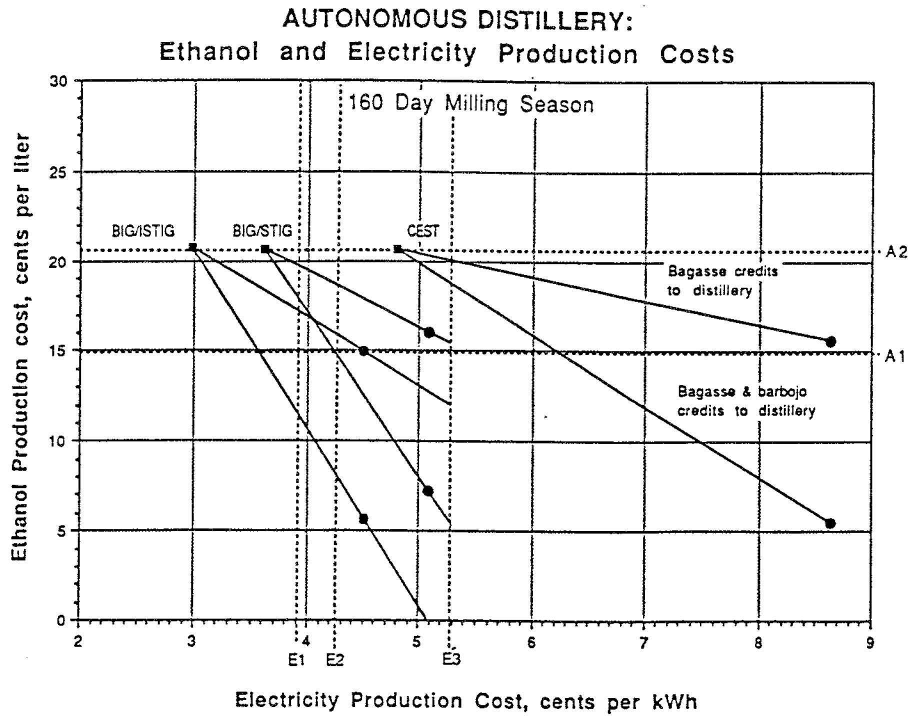


Figure 9a.

The Cost of Ethanol and Electricity Using Alternative Cogeneration Technologies for Brazilian Autonomous Distilleries Operated 160 Days per Year

For cogeneration based on using, as fuel, bagasse during the milling season and barbojo during the off-season. For each technology, a range of ethanol and electricity costs is shown, corresponding to different prices for the cane residues. As the residue price increases (moving from left to right along each line), the cost of electricity increases and the corresponding cost of ethanol decreases, because it is assumed that the distiller takes the increased revenues as a credit against the cost of producing alcohol. Two lines are shown for each technology. The top line represents the case where only bagasse revenues are credited against the alcohol cost. This would be the case if the barbojo were purchased from independent cane growers. The steeper line is for the case where the distiller owns the cane fields and sells barbojo as well as bagasse to the cogenerator. The point where these lines meet indicates the ethanol and electricity costs when no net payments are exchanged between the cogenerator and the distiller: bagasse is given to the cogenerator in exchange for the steam and electricity needed to run the distillery. The black dot on each line is for a maximum residue cost to the cogenerator (purchase price plus the cost for processing the residues into a gasifiable form) of $3/GJ, the estimated cost of delivered, air-dried woodchips in Brazil, for the case where the cogenerator has access to woodchips as an alternative biomass feedstock during the off-season.

Also shown are: the prices at which ethanol would be competitive at the present world oil price as a neat fuel (A1), assuming a liter of alcohol is worth 0.84 liters of gasoline, and as an octane-enhancing additive (A2), assuming a liter of alcohol is worth 1.16 liters of gasoline; and the prices at which the cogenerated electricity would be equal to the operating cost of an oil-fired power plant at the present world oil price (E1) (assuming a heat rate of 13,120 kJ/kWh and a fuel oil price of $2.63/GJ), the busbar cost of a new hydroelectric plant (E2) (assuming a capital cost of $1500/kW), and the busbar cost of a new coal plant (E3), assuming a capital cost of $1400/kW and a coal price of $1.7/GJ.

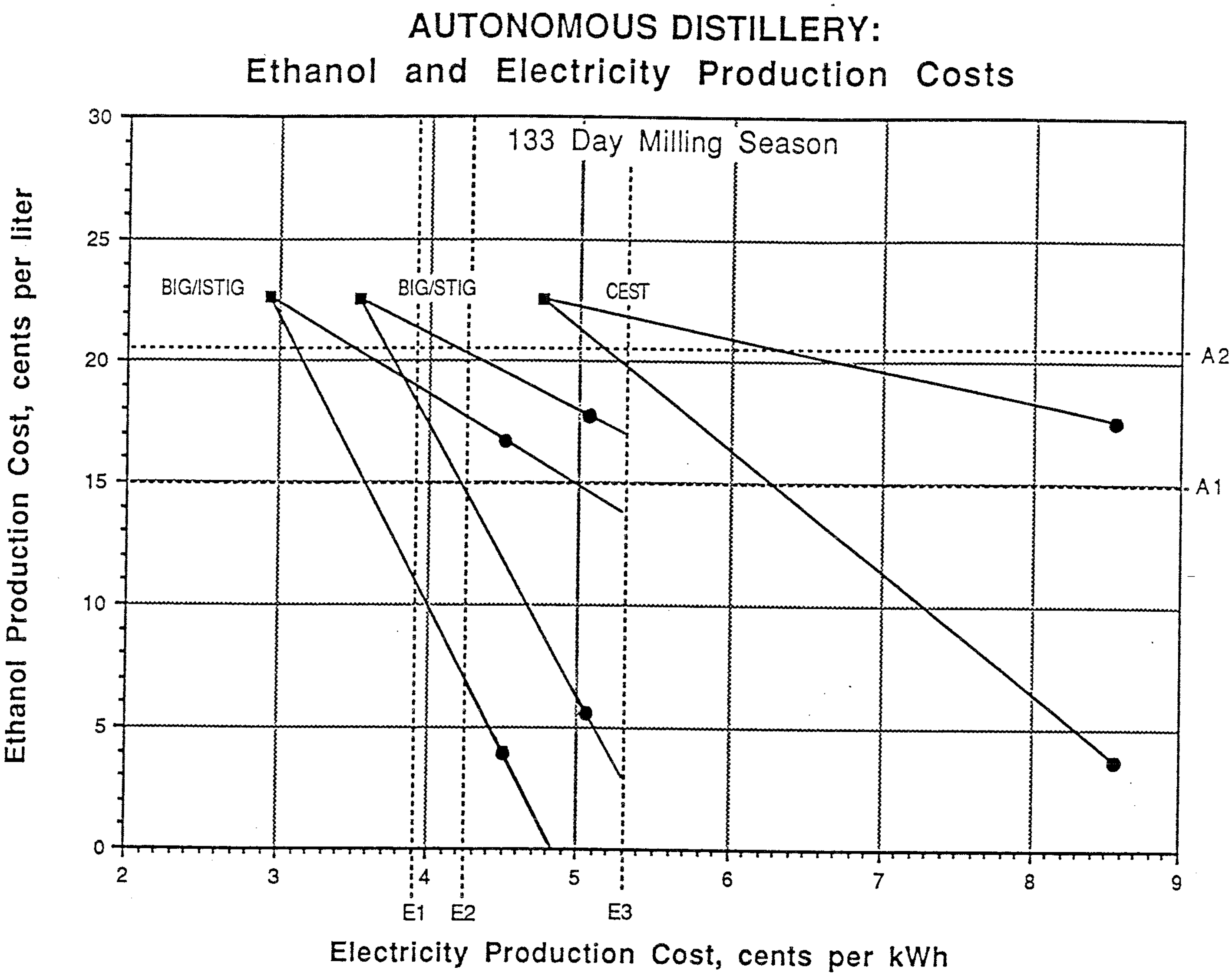


Figure 9b.

The Cost of Ethanol and Electricity Production Using Alternative Cogeneration Technologies for Brazilian Autonomous Distilleries Operated 133 Days per Year

With a 160-day milling season (Figure 9a) only about 60-70% of the barbojo can be used for power generation in the off-season (Figure 8). A larger percentage of the barbojo could be used if the milling season were shorter. For a 133-day milling season, 80% of the barbojo could be used with BIG/ISTIG technology (Figure 8). The shorter milling season leads to a lower capacity utilization factor for the distillery, which would tend to drive up the cost of alcohol. But if the distiller owns the cane fields, the extra revenues he could get from barbojo sales would more than compensate for the lower distillery capacity factor, making the short milling season option economically attractive.