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Summary Report on Visit to Cuba
June 20-24, 1994

Contents

Background

Cuba has a sugarcane production capacity of some 80 million tonnes per year. At this level of cane production, if Cuba were to adopt high-pressure steam-turbine cogeneration technology at all of its sugar mills, it could produce an amount of electricity from sugarcane biomass residues (in excess of that required to operate the sugar mills) twice the total present (depressed level of) utility electricity production from oil. If biomass-gasifier/gas turbine technology were used, the electricity potential is quadruple present electricity production from oil. (See Appendix.) I went to Cuba to try to better understand the prospects for tapping some of this potential and to try to identify potential launch projects. This report summarizes my visit.

I was invited to Cuba by Ing. Jorge Santamarina of the Comision Nacional de Energia (CNE) and was hosted by the Ministry of Sugar while there. Santamarina and his colleagues in several government ministries and at universities were familiar with CEES work on biomass-gasifier/gas turbine power generation and were very interested in learning more firsthand. I had extensive discussions with individuals in the Sugar Ministry (MINAZ); the Basic Industry Ministry (MINBAS), which is responsible for electric power generation: the Ministry of Economy and Planning (MEPLAN); the Ministry of Science, Technology, and Environment (MCTE); and the Ministry of Higher Education. I also met with Pedro Miret, one of Castro's 5 Vice Presidents on the Council of State, together with the leader of a quasi-governmental group called the National Movement for Science and Technology Forum ("The Forum"). I also met with the executive director of the non-governmental Cuban Association of Sugar Technologists (ATAC), and researchers from three major universities. I also had an opportunity to visit one sugarcane cleaning station, a technology that is uniquely Cuban (and extensively used there) for separating trash (tops and leaves) from the cane stalks. Unfortunately the crushing season was over, but I did get to see (and keep) a videotape of the harvest and cleaning operations. Though meetings occupied most of my time there, I was treated to a walk around old Havana, a quick look at the Museum of the Revolution, a viewing of the 300-year tradition of the daily 9 p.m. canon firing at the former Spanish fort standing in Havana, and an evening at the Tropicana.

Prospects for cane energy development in Cuba

In retrospect, the first meeting I had on Monday at MINAZ characterized well what I saw during the whole of my trip: there is an intensity of interest and unity of voice among diverse institutions in and out of the government relating to the development of electricity production from sugarcane to replace oil-fired power and make the sugar industry more competitive. At this meeting I talked for nearly 3 hours with a group of individuals that constituted a self-labeled "cane-power task force" formed to develop and push the idea of cane power within the government. The meeting was in the office of the Vice Minister for Development, Ing. Gilberto Llerena, who co-authored a paper on the idea of electricity export from sugar mills some 15 years ago with a colleague from the Dominican Republic. Additionally in the meeting were Ing. Paulino Lopez Guzman (MINAZ, science and technology branch), Ing. Francisco Cruz Rodriguez (MINAZ, energy branch), Ing. Jorge Santamarina (CNE), Ing. Jorge Luis Isaac (MINBAS, electric utility branch), Lic. Julio Torres (MEPLAN), and Dr. Antonio Valdes (MCTE). This "task force" appeared to be a very cohesive group, and each of its members is involved in work within their home ministry aimed at developing cane power for Cuba.

Hard currency problems

With one exception, the barriers to developing cane power in Cuba are modest by any standard, as I discuss below. Access to capital, even for relatively small prefeasibility studies that require hard currency, is a very major barrier. Primarily because of the US embargo, Cuba is not eligible for loans from the World Bank, the IMF, and some other US-influenced assistance agencies. Interestingly, however, I was told there is one GEF project in Cuba, and major UNDP projects have been (are?) ongoing. I was told that the UNDP has been pleased by their projects in Cuba because the projects have generally achieved stated objectives. Because of the scarcity of capital, any money that does become available to Cuba will have many competing demands. For example, Vice Minister Llerena told me that if he had $10 million today, he would buy fertilizers for the sugarcane fields, because he would be sure of recovering the investment in two years.[1] Clearly, external financing will be required to develop cane-electricity projects, especially if some import of equipment is required. One question that I did not get satisfactorily answered was how difficult it would be for foreign investors to recover their investments in dollars. Evidently, this issue has been resolved in some other areas: the Mexican telephone company recently bought half of the Cuban telephone system, and oil companies from Brazil to Sweden have oil exploration rights.

Positive factors

Aside from the problem of capital scarcity, the barriers to the development of cane power in Cuba appear to be much lower than in any other country that I am familiar with. In particular, institutional, technical capacity, and infrastructure constraints are much less than in most countries.

The sugar producers (led by MINAZ) want to develop cane power, as does the electric utility (under MINBAS). In other countries, many sugar producers have told me that they are *sugar* producers, not electricity producers, and electric utilities have not been interested in cane power for a variety of reasons, from lack of control to lack of the "glamour" of fossil or nuclear power. These attitudes are starting to change in many countries, but they appear to be almost non-existent in Cuba. In fact, some 76 sugar mills there (about half the total) are already

[1] Cuba's cane production this past season was the lowest for many decades due to shortages of fertilizers and fuel for harvesting equipment. It was about half the historical peak of some 80 million tonnes (reached in the mid-1980s). (M. Whitefield, "Cuba's sugar harvest is worst in 30 years," *Miami Herald*, June 24, 1994.)

exporting some power (69 GWh during the most recent crushing season--about 10% of that generated at mills from bagasse) to the grid and are receiving 5 cents per kWh for the power. Ten mills are using trash as a regular boiler fuel. Essentially all sugar mills are already connected to the grid.

Cuba is also unique in that it has upwards of 1000 cane cleaning stations that process essentially all of the cane that is crushed in its 156 factories. The cleaning stations are generally not adjacent the mills, but are connected to mills by a rail network. The dedicated sugarcane rail system contains more track (> 8000 km) than the passenger/freight rail system. The cleaning stations take in green machine-cut cane (76% of cane is harvested this way) or green manually-cut cane. Trash is removed from the stalk and blown out into a storage area. The stalks travel along a conveyor to awaiting rail cars. The predominant practice today is to incinerate the trash at the cleaning station to reduce the "waste" volume. Interestingly, mechanical harvesting and cane cleaning stations were developed after 1959 in the face of acute labor shortages.

I saw much evidence of the enthusiasm and commitment to the development of cane power in Cuba, as well as technical capabilities and characteristics that are conducive to pursuing this goal:

- As a result of chronic and extended blackouts caused by a shortage of oil for electricity generation, the government has made the development of sugarcane-derived electricity a top energy priority for the country. The priority this area is receiving accounts in part for the existence of the "cane energy task force" (discussed earlier).

- "The Forum," which is under the supervision of Vice President Pedro Miret, is evidently an important organization in steering the country on science and technology decisions. The Forum's highest priority area is renewable energy from sugarcane. They seem to be especially interested in electricity from cane using "leading technologies." There is an annual national meeting of the Forum (in Dec. or Jan.), which Fidel usually attends. (I was invited to a meeting in late October that will focus on the topic of renewable energy and generate inputs for the national meeting.)

- CNE, the energy commission, which was formed in 1989 (?) as a special advisory body to the National Assembly, features three full-page pictures of sugarcane (including one on the cover) in its June 1993, 25-page summary of its program on the development of indigenous energy sources.

- MINBAS has committed a full-time person at the level of Director (inside UNE--Union Electrica--the electric utility division) to the development of biomass power generation projects.

- MINBAS has a special consulting and engineering group, "Energoproyecto," which, among other studies, has undertaken detailed techno-economic assessments of alternative strategies for using trash as a fuel in utility power plants that are presently fired with residual oil. The assessment that I saw seemed rigorous on both technical and financial aspects.

- An extremely detailed sugarcane mass balance, based on field and mill measurements, has been worked out by Ing. Felix J. Perez Egusquiza, MINAZ's "trashman". As a national average, the trash (bone dry basis) available at harvest (dry leaves, green leaves, tops, and dead cane) is estimated to be equivalent in mass to 14% of the mass of the bare wet cane stalks entering the mill (see Appendix). This is comparable to the trash levels found in Brazil.[2]

- MINAZ, which manages essentially all aspects of sugar production in Cuba, overseas many research, development, engineering, and manufacturing activities, including equipment manufacturing and IPROYAZ (Instituto Proyeto Azucar), the Sugar Design and Engineering Institute that works in and out of Cuba.[3] The Design and Engineering Institute recently designed a sugar factory for Nicaragua (now built and operating) that has a 25 MW_e cogeneration plant that operates on bagasse during the crushing season and eucalyptus from plantations during the off-season.

- IPROYAZ (under MINAZ) and ENERGOPROYECTO (under MINBAS) would jointly design sugar mill cogeneration systems for electricity exports to the grid.

- The Ministry of Science, Technology and Environment has launched a research program to develop Cuban expertise relating to biomass gasification and gas turbine systems.

- Cuban sugar mills are relatively large, which should help improve the return on any cogeneration investment that might be made. Out of 156 mills, some 25 to 30 have capacities to crush 10,000 to 12,000 tonnes of cane per day; at least 10 with capacities of 7,000 tonnes per day (all built since 1959); and some 60 mills with capacities of 4,000 tonnes per day. The smallest mill, Pablo Noriega (an experimental facility), has a capacity of 1,100 tonnes per day.

- There were 70 or 80 people in attendance at the seminar I gave at the Jose Antonio Echeverria High Polytechnic Institute (ISPJAE), 20 or so of whom stayed on for a working session I ran to go through some case-study calculations.

Cuba's 2-track interests in cane power development

The people I spoke with at MINAZ indicated a strong interest in following two parallel approaches to the development of electricity from sugarcane.

For the near term, they are actively interested in using high pressure steam turbine cogeneration systems to increase the electricity exports from sugar mills. Toward this end,

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[2] Cuba is also doing a small amount of work on developing cane varieties for fiber rather than sugar. Invitro techniques permit them to develop new varieties in about 4 years, rather than 10 years with traditional field methods. MINAZ indicated that they had achieved a productivity of 60 dry tonnes per hectare per year on small plots with one "fiber-cane." Herbicide and pesticide (and maybe fertilizer) application rates are lower than with "sugar-cane."

[3] Cuba has the capacity to manufacture all equipment used in its sugar mills. In cogeneration technology, these manufacturing capabilities are presently limited to boilers with a maximum pressure of about 30 bars. Boiler pressures of 60 to 80 bar characterize high pressure steam cogeneration systems that would permit substantial quantities of electricity exports from sugar mills. The boiler manufacturing capacity in Cuba today is for 30 boilers per year (28 bar pressure) with a steam flow of 60 tonnes per hour.

MINAZ recently began a very preliminary "opportunity study" at one sugar mill, the Sergio Gonzalez mill (4,800 tonne per day milling capacity), to determine whether it would be worthwhile to pursue a prefeasibility study for the installation of a high-pressure steam turbine cogeneration system there. (See the Appendix for some detailed calculations for this mill.) They are working with a French company in some fashion on this--the same company that was involved in the installation of high pressure steam systems on the island of Reunion.

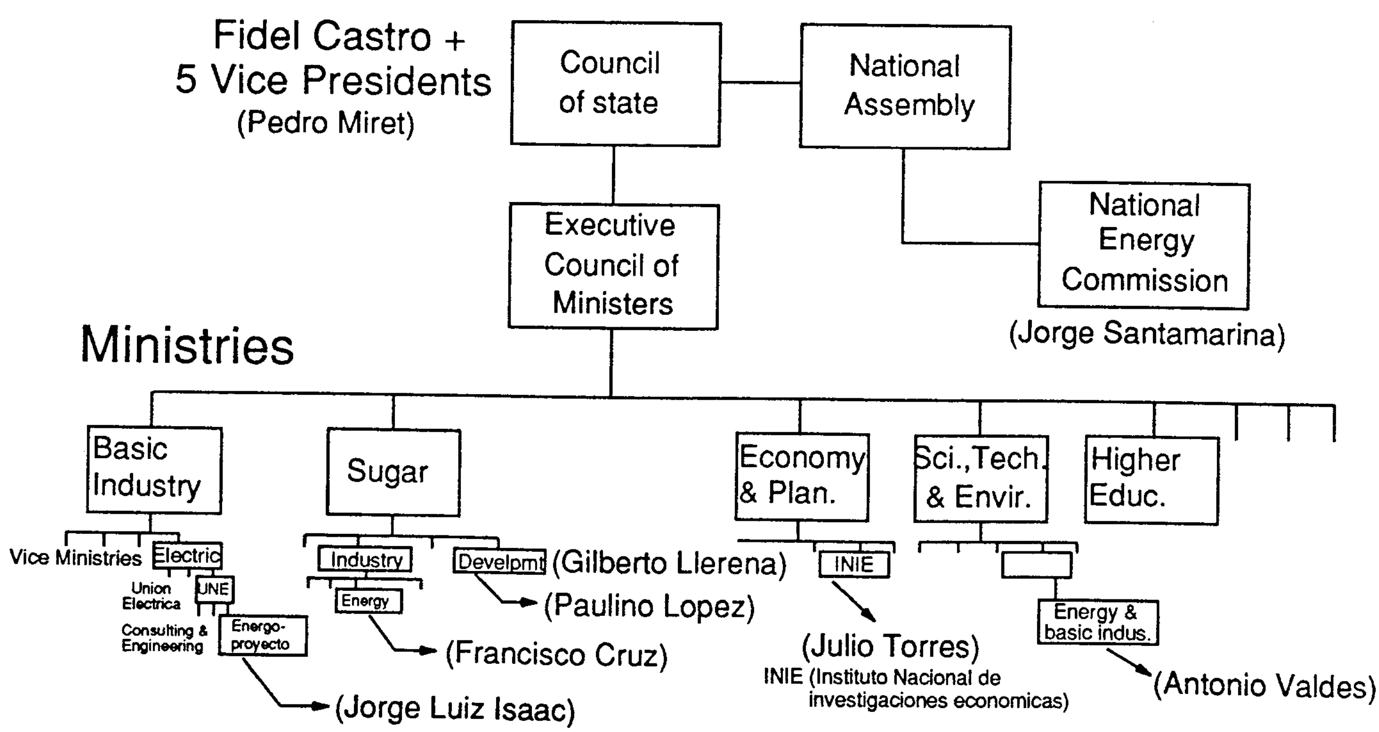
For the longer term, MINAZ would like to begin laying the groundwork and establishing the capability to install biomass-gasifier/gas turbine cogeneration systems. They would welcome an opportunity to participate in a BIG/GT demonstration where the fuel would be sugarcane bagasse and trash.

A major advantage that Cuba brings in pursuing both of these approaches is the fact that cane trash recovery is routinely and widely practiced there. In any other country, the development of trash recovery systems would involve major changes in agronomic practices and infrastructure. The other major advantage that Cuba would have, as was pointed out several times to me by Cuban colleagues, is the collective decision making process among all relevant ministries and other organizations, as well as the consensus that already exists widely in the government on the need to develop cane power.

Individuals with whom I met

The following are individuals with whom I met. To understand the relative positions of the members of the "cane energy task force," I've sketched the following organizational chart for the government, as I understood it to be from conversations in Cuba:

Organizational chart



Names and positions

Council of State (Consejo de Estado, fax: same as for MINBAS)
Comdte Pedro Miret, Vice President. Overseas "the Forum". Reports to Fidel.
Eugenio Maynegra Alvarez, Advisor to Miret and Director of "the Forum" (industrial engineer).

Ministry of Basic Industry (fax: 53-7-335345)
Ing. Rodrigo T. Ortiz Gomez, Vice Minister. Responsible for electricity generation.
Ing. Eduardo Sieczka, Director, Energoproyecto under MINBAS' electrical division (UNE).
Ing. Jorge Luis Isaac. Project specialist with Energoproyecto; on "cane energy task force".

Ministry of Sugar. Ministerio de la Industria Azucarera, Calle 23 No. 171, Apto. 6413, Vedado, La Habana.
Gilberto Llerena, Vice Minister in charge of energy matters; on "cane energy task force.
Rafael Suarez Rivacoba, Director of Science and Technology
Ing. Paulino Lopez Guzman C. Dr., Science and Technology division under Rivacoba; on "cane energy task force". ph: 53-7-324174/fax: 53-7-333193
Ing. Francisco Cruz Rodriguez. Electrical engineer in energy division; on "cane energy task force".
Ing. Felix I. Perez Egusquiza, Does assessments for MINAZ, especially regarding trash.

Ministry of Science, Technology and Environment (formerly the Academy of Science). Capitolio Nacional, Industria e/ Dragones y San Jose, H. Vieja, La Habana, CP 10200.
Dr. Jose M. Oriol Guerra, Vice Minister.
Dr. Antonio Valdes Delgado, Energy Division; on "cane energy task force".
Dr. Barbara Garea Moreda, Biomass and energy specialist.

Ministry of Economy and Planning
Julio Torres Martinez, Institute for Economic Research (INIE/JUCEPLAN); on "cane energy task force"

National Energy Commission (ph: 53-7-30-0825 or -0835/fax: 53-7-333387)
Dr. Manuel Aguilera, Executive Secretary.
Ing. Jorge Santamarina, on "cane energy task force".

Ministry of Higher Education
Dr. Ing. Hector Perez de Alejo, technical assessor (energy conservation in sugar mills) ph: 53-7-33420/36655; fax: 53-7-333090/333295.

Cuban Society of Sugarcane Technologists (Asociacion de Tecnicos Azucareros de Cuba)
Oscar Almazan del Olmo, President. Also executive secretary of International Society of Sugarcane Technologists (ISSCT).
Dr. Antonio Valdes Delgado, Vice President for Energy and the Environment (same Valdes as in Science, Technology, and Environment Ministry,

Others
Dr. Carlos M. De Armas, Research Institute for Sugarcane Byproducts (ICIDCA), ph: 53-7-99-5938/fax: 53-7-338326.
Dr. Ing. Angel M. Rubio Gonzalez, Director, Centro de Estudio de Termoenergetica Azucareta (CETA), Universidad Central de Las Villas
Dr. Ing. Pablo R. Roque Diaz, CETA.
Dr. Omar E. Herrera Martinez, Director, Centro de Estudios de Tecnologias Energeticas Renovables (CETER), Instituto Superior Politecnico Jose Antonio Echeverria (ISPJAE).
Dr. Ing. Anibal Boccoto Nordela, Centro de Estudios de Energia y Medio Ambiente, Insituto Superior Tecnico de Cienfuegos.

Miscellaneous notes

- MINAZ in 1993 owned 73% of sugarcane (27% controlled by private cooperatives); in 1994, 100% of cane is owned "privately" and MINAZ owns 73% of the cane lands (rents to farmers). Now 100% of cane production is in hands of Union of Basic Cane Producers (UBPC), which has good relations with MINAZ.
- On-site electricity consumption at sugar mills often includes electricity for the community, for irrigation, for cane cleaning stations, etc.
- 10 new mills (7000 tc/day each) built since Revolution.
- Biological injections developed in Cuba to allow long-term bagasse storage with 7-10% loss (instead of normal 20%).
- Trash has six times the ash of bagasse.
- Cuba presently has spare oil-fired capacity (due in part to shortage of oil), but this will not last. MINBAS is debating internally whether to invest in new oil-thermal plants or develop cane power. (Coal is considered too expensive and not environmentally preferable.) In either case, foreign investment is needed.
- The Ministry of Science, Technology and Environment is involved in studies on steam consumption reduction in sugar mills, bagasse combustion efficiency improvement, alternative uses for trash briquettes for energy (and transportation alternatives), and lab-scale biomass gasification.
- Steam boiler pressures at sugar mills have increased from 18 to 28 bar over the last 20 years. Much greater investments (including in boiler manufacturing capacity) are needed to go beyond this level of pressure.
- The "Forum" is a totally voluntary organization (with little administrative overhead) that seeks to good identify ideas generated at the worker level up to research institute level and to replicate and disseminate the ideas. The Forum facilitates communication among different branches of government as well as among non-governmental entities.
- The Central University of La Villa sits in Villa Clara province, which contains 27 sugar mills. The UCLV has a Sugar Industry Thermal Engineering Research Center that is involved in various aspects of energy and the sugar industry, including trash recovery.
- One person at UCLV indicated that 50-70% of trash can be removed from the field without negative agronomic consequences.
- Visit to a cane cleaning station. Capacity = 100 tc/day, requiring 10 kWh_e/tc. Maximum size of a cleaning station is 4000 tc/day. Typically operates 12 hours/day.
- Visit to prototype whole-leaf trash briquetting plant. Capacity = 2.5 tonnes/hr of briquettes at 15-30% moisture content, 350-400 kg/m^3. Electricity use is 8 kWh/tonne of briquettes.
- ISPJAE (in Havana) has Center for the Study of Renewable Energy Technologies. Industry-university cooperation is very close.
- Sergio Gonzalez mill (4800 tc/day) is being considered for a 27 MW_e high-pressure steam turbine cogeneration systems (80 bar, 520°C). Electricity production would be 85 kWh/tc during milling season. (See Appendix for more discussion of Sergio Gonzalez.)
- Cuban harvesting machines are like Australian ones (cane cut into 30 cm billets and trash centrifugally separated during harvest), but without blades to cut tops off ahead of machine.
- When there is sufficient electricity in Cuba, 60% of sugarcane is irrigated.
- Cane grows 12-14 months; harvest time is late December to late April/early May.
- Invitations received to return to Cuba to participate in: *(1)* The Forum: Late October or early November sub-national meeting (one of a series on selected topics) on renewable energy, leading up to big national meeting (on energy and other topics) in December or January. *(2)* Earth Conference on Biomass for Energy, Development and the Environment (Jan. 10-14, 1995),

David Hall is one of the organizers. *(3)* Scientific Conference on Engineering and Architecture (29 Nov - 2 Dec) at ISPJAE (engineering and architecture schools affiliated with the Univ. of Havana). *(4)* Conference on Industrial Thermal Engineering at Sugar Industry Thermal Engineering Research Center (15-16 Nov) at Central University of Las Villas (UCLV). *(5)* Biennial National Conference of the Cuban Association of Sugar Technologists (Nov. 94 at Varadero). *(6)* Open invitation to me and/or Bob Williams from CNE, MINAZ, MCTE, etc.

Documents in hand

Antonio Valdes, Antonio Aguilar, and Marta Salermo, "Energia neta obtenible a partir del uso de los residuos agricola de al cosecha," Ministry of Science, Technology and Environment, Havana, (no pub. date, rec'd. June 23, 1994).

Comision Nacional de Energia, *Programa de Desarrollo de las Fuentes Nacionales de Energia*, Havana, June 1993.

Energoproyecto, "Generacion de Electricidad con Biomasa Canera Como Combustible Cte. Raul Martinez Vicente, Ciego de Avila: argumentacion del proyecto," MINBAS, 25 Jan. 1994.

Ing. Felix J. Perez Egusquiza, "Balanco Nacional de Paja de Cana," Santa Clara, Cuba, June 20, 1994.

Direccion Industria Basica, *Los Residuos Agricolas de la Cosecha Canera Como Fuente de Energia Renovable: Informacion Tematica*, Academia de Ciencias de Cuba, Havana, August 1993, 55 pp.

Ministry of Sugar, *Cosechadoras de Cana, Centros de Acopio, Estaciones de Limpieza*, video cassette (mechanical harvesting, cane cleaning station), rec'd June 1994.

Ministry of Sugar informational brochures: "Union de Investigacion Produccion de la Celulosa de Bagazo," "Union de Empresas Mecanicas (UEM)," "Cuban Institute for Research on Sugarcane By-Products (ICIDCA)," "Cuban Sugar Research Institute (ICINAZ)," "Cuba: Its Mills, Refineries, and Bulk Loading Terminals."

Cuban Sugar Technologists Association, *ATAC, Revista de la Asociacion de Tecnicos Azucareros de Cuba*, 4 sample issues.

Centro de Estudio de Termoenergetica Azucarera, "Proyecto de Colaboracion International," (a proposal), Universidad Central de Las Villas, 1994.

Instituto Superior Politecnico Jose Antonio Echeverria, "Resultados Cientificos Mas Significativos de 1993," Havana.

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Appendix
Calculation of the Sugarcane-Biomass Electricity Potential in Cuba

Contents

Introduction

This appendix provides detailed calculations of the cogeneration performance of high-pressure steam turbine and biomass-gasifier/gas turbine systems in the context of Cuban sugar mills. A case study calculation is carried out for one specific Cuban sugar mill, Sergio Gonzalez, which is presently being evaluated as a candidate site for installation of a high-pressure steam turbine cogeneration system. Calculations relating to the economics of export electricity production are also presented. Finally, an estimate is presented of the all-Cuba potential for electricity production from sugarcane-biomass and for the corresponding oil import savings that could accrue through replacement of oil-fired electricity with cane-derived power.

Performance estimates of alternative cogeneration technologies

High-pressure steam-turbine systems. The performance of a biomass-fired condensing-extraction steam turbine (CEST) cogeneration plant is characterized by assuming the following: steam input to the turbine of 319 tonnes per hour at 62 bar and 400°C, isentropic turbine efficiency of 75%, condenser pressure of 0.06 bar, electric generator efficiency of 95%, and an overall efficiency of electricity production from biomass in the full-power mode (no process steam production) of 21% (higher heating value basis). (These conditions give performance that is close to that for a CEST plant described in [1] using wood wastes with 50% moisture content as the fuel.)

In the full-power mode, the output of this system is 73.5 MW_e,[1] corresponding to a fuel input rate of 350.2 MW_b (higher heating value basis). In the full-cogeneration mode, all 319 t/h of steam are assumed to be extracted at a pressure of 2 bar.[2,3] The system still consumes 350.2 MW_b of biomass fuel, producing 44.5 MW_e.[4] In this mode, the fractions of biomass energy converted to electricity and to process steam, respectively, are 12.7% and 49.7%.

To put the performance of CEST technology in the context of a sugar mill that requires saturated process steam at 2 bar, it is necessary to know the fuel availability at such a mill. If the amount of bagasse available at the mill is assumed to be 135 dry kg per tonne of cane entering the mill[5] (and bagasse is assumed to have an energy content of 19 MJ/dry kg), then bagasse energy available for cogeneration is 2,565 MJ/tc, where tc is a metric tonne of sugarcane that enters the crushing mill. In the full cogeneration mode, the electricity production per tonne of cane would be 91 kWh/tc, while the steam production would be 649 kg/tc.[6] In the full-power mode the electricity production would be 150 kWh/tc.

For simplicity, the electricity and process steam production of CEST technology (at a mill where a fixed amount of process steam is required) is assumed to be described by a linear relationship between the full-cogeneration and full-power operating points, as shown in Fig. A1.

Biomass-integrated gasifier/gas turbine systems. In earlier work [3], the performance of a biomass-integrated gasifier/gas turbine (BIG/GT) system was described for a cycle based on a steam-injected gas turbine. It now appears that the first BIG/GT cycle that will be demonstrated will be a BIG/GT combined cycle (BIG/GT-CC) [4]. A performance estimate for this technology is developed here, based on the heat and mass balance appearing in [5] for a BIG/GT-CC producing power only. The energy balance for this cycle is reproduced here as Fig. A.2. This system involves a pressurized

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[1] The inlet enthalpy of the steam is 3173.3 kJ/kg. The enthalpy at the condenser pressure is 2008.8 kJ/kg, assuming isentropic expansion. Thus, kW_e = (319 t/h)*(3173.3-2008.8 MJ/t)*(0.75)*(0.95)/(3600 s/h).

[2] This was indicated to be the process steam pressure at the Sergio Gonzalez sugar mill in Cuba [2].

[3] In practice, some steam flow would be required through the low-pressure section of the turbine (for cooling) and through the condenser. For this preliminary calculation, this steam flow is neglected here.

[4] The inlet enthalpy of the steam is 3173.3 kJ/kg. The enthalpy at extraction point is 2,469 kJ/kg, assuming isentropic expansion. Thus, kW_e = (319 t/h)*(3173.3-2469 MJ/t)*(0.75)*(0.95)/(3600 s/h).

[5] An estimated average for Cuban sugar mills [2].

[6] Electricity production = 90.5 kWh_e/tc = (0.127 kWh_e/kWh_b x 2565 MJ_b/tc)/(3.6 MJ_b/kWh_b), and steam production = 649 kg_s/tc = (319,000 kg_s/hr)/{(350.2 MJ_b/s)*(3600 s/hr)/(2565 MJ_b/tc)}. The subscripts *e*, *b*, and *s* refer to electricity, biomass and steam.

circulating fluidized-bed gasifier, syngas cleanup at elevated temperature, gas combustion in a modified General Electric LM2500 gas turbine, steam production at 60.3 bar, 443°C from a combination of syngas cooling and gas turbine exhaust heat, and finally expansion of the steam through a condensing steam turbine.

The full-power mode of operation is assumed to be as shown in Fig. A.2. Net electricity output is 28.8 MW_e with an efficiency of 36.6% (higher heating value basis), corresponding to a biomass fuel input of 78.7 MW_b.

To estimate the full-cogeneration performance, it is assumed that steam is expanded in the steam turbine to 2 bar pressure, rather than the 0.056 bar indicated in Fig. A.2. The electricity production from the steam turbine is then estimated to be 6.4 MW_e, compared to the 10.6 MW_e shown in the figure. Total steam production is 12 kg/s at 2 bar. The total electricity production (including that from the gas turbine, but excluding auxiliary consumption) would be 24.6 MW_e, corresponding to 31.3% of the biomass fuel input.

The BIG/GT-CC performance in the context of a sugar mill would be characterized as follows. In the full-cogeneration mode, the electricity and steam production per tonne of cane would be 223 kWh/tc and 391 kg/tc, respectively.[7] The electricity production in the full-power mode would be 261 kWh/tc. These characteristics are summarized in Fig. A.1.

Cogeneration technology performance relative to sugar mill energy demands

The operating characteristics of the cogeneration system at a sugar mill during the crushing season will depend primarily on the steam demands of the mill, since these must be met in order to produce sugar. As is evident from Fig. A.1., whether CEST or BIG/GT-CC cogeneration technology is considered, the lower the steam demand, the higher the electricity production that is possible at the mill. Electricity in excess of the mill's demands would be available for sale by the mill, for example to the national grid.

Steam demands at different mills vary significantly. Cuba has a number of sugar mills in which the cane crushing units are electrically driven, which eliminates the need for steam at elevated pressure. The demand for low-pressure (2 bar) steam at the Sergio Gonzalez mill is 380 kg/tc.[8] For comparison, the Monymusk mill in Jamaica has an estimated low-pressure steam demand of 374 kg/tc [3]. For Monymusk, retrofits that could be made to the mill could reduce the steam demand by nearly 50%, to 209 kg/tc [3]. If comparable steam saving retrofits can also be made to the Sergio Gonzalez mill, steam demand would be reduced to about 210 kg/tc.

Because of the electrification of the crushing mills, electricity demand at Sergio Gonzalez is relatively high, 27 kWh/tc, compared to the Monymusk mill that consumes 13 kWh/kg (because the crushing mills are steam driven) [3].

Case study of Cuba's Sergio Gonzalez Mill

Based on the above calculations, the electricity production potential at a specific mill can be estimated. The mill selected for this illustration is the Sergio Gonzalez mill in the province of

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[7] Electricity production = 223 kWh_e/tc = (0.313 kWh_e/kWh_b x 2565 MJ_b/tc)/(3.6 MJ_b/kWh_b), and steam production = 391 kg_s/tc = (12 kg_s/s)/{(78.7 MJ_b/s)/(2565 MJ_b/tc)}. The subscripts *e*, *b*, and *s* refer to electricity, biomass and steam.

[8] The crushing mills at the Sergio Gonzalez mill are currently driven by steam reciprocating engines, which require higher pressure steam. Plans are to replace these with electric motors in the near future, after which the steam demand will be only for the 380 kg/tc of low-pressure steam.

Matanzas. This mill is currently the focus of an opportunity study for the installation of a high-pressure steam turbine system. The salient characteristics of the mill are as follows. The length of the off-season and anticipated capacity factor are included in this set of characteristics because off-season operation of the cogeneration plant in the full-power mode using cane trash as fuel will be considered.

Cane crushing capacity:	4,800 tc/day
Crushing season:	150 days
Capacity factor:	85%
Bagasse availability:	135 dry kg/tc
Energy demands:	
Present	
Steam:	380 kg/tc @ 2 bar
Electricity:	27 kWh/tc
Improved	
Steam:	210 kg/tc @ 2 bar
Electricity:	27 kWh/tc
Off season characteristics:	
Number of days:	215 days
Capacity factor:	85%

With the above characteristics of the Sergio Gonzalez mill and the cogeneration performance characterstics shown in Fig. A.1., the electricity export potential of the Sergio Gonzalez mill is shown in Table A.1 for alternative cogeneration technologies and alternative mill energy demands. In this table, it is assumed that the cogeneration facility operates during the off-season with a supplemental fuel, ideally sugar cane trash that is today either incinerated at cane cleaning stations in Cuba or that is left in the field. Fig. A.3 summarizes the electricity export potential for alternative cogeneration and sugar-mill systems. With CEST systems operating year-round at a sugar mill with reduced process steam demands, the export electricity production potential is over 300 kWh/tc, compared to essentiall zero exports today. With BIG/GT-CC technology, the electricity exports would be roughly double the level for the CEST.

Assuming the energy content of dry trash is the same as that for dry bagasse, the quantity of trash that will be needed to operate during the off-season will be equal to the quantity of bagasse used during the on-season, multiplied by the ratio of the length of the off-season to that of the on-season. Thus, since the bagasse used is 135 dry kg per tonne of biomass as cane that enters the mill, the amount of trash required will be 135*(215/150) = 194 dry kg/tc. For comparison, the estimated average total amount of trash (in the field before harvest) that is associated with each tonne of biomass delivered to the mills as cane is 140 dry kg/tc.

The amount of trash associated with sugarcane in Cuba is calculated from Table A.2, assuming that the residues delivered to the mill with the cane are counted as part of the mass of cane. Thus, the mass of residues that are not delivered to mills at present is the total residues (top right-most number in Table A.2) less the residues that are delivered to the mill. The average dry matter content of these residues is assumed to be 51.8% (see note *(b)* in Table A.2).

If this estimate of the trash availability is correct, there would be insufficient trash associated only with the cane delivered to the Sergio Gonzalez mill to operate for the full off-season. Some additional trash supply would be needed. This might be trash associated with cane that goes to other mills. Alternatively, the capacity of the cogeneration facility could be reduced, so that some excess bagasse accumulates during the milling season. This bagasse could then be used to augment the trash during off-season operation.

Economics of export electricity production

An estimated unit cost of generating electricity in excess of process needs at a sugar mill cogeneration facility can be calculated using the following simplifying assumptions.

The capital cost ($\$/kW_e$) for CEST technology is estimated for U.S. conditions[9] to be $6523*(MW_e)^{-0.32}$, which is based on *(i)* a cost of $\$2358/kW_e$ for a 24 MW_e biomass fired power plant [6] and *(ii)* a captial cost scale sensitivity as estimated for coal-fired steam plants [6]. The capital cost for BIG/GT-CC technology is uncertain, but target costs for the commercial version of the 25 to 30 MW_e unit that will be demonstrated in Brazil is $\$1300/kW_e$ to $\$1500/kW_e$ [4].

For simplicity, operating and maintenance costs (excluding fuel) are assumed to be \$0.005/kWh for both CEST and BIG/GT-CC technology. This value is consistent with indications given elsewhere for both of these technologies [3,4].

Finally, the cost for the bagasse and trash to fuel the cogeneration facility must be determined. In the case of the Sergio Gonzalez mill desribed above, the annual bagasse and trash consumption would be 82,620 dry tonnes and 118,422 dry tonnes, respectively. Thus, annual fuel cost (in dollars) would be $(82,620*P_{bag})+(118,422*P_{tsh})$, where P_{bag} and P_{tsh} are the price (in \$/dry tonne) paid by the cogeneration plant for bagasse and trash, respectively. In the simplist case, the cost for bagasse might be charged to sugar production, rather than to export electricity production. Some estimates have been made for the cost of recovering and delivering trash to sugar mills in Cuba. One estimate is that it could be delivered in loosely-briquetted form (350 kg/m^3, 40% moisture content) from a cane cleaning station to a sugar mill at a cost of \$8.3/dry tonne, or \$0.43/GJ.[10]

With the above capital, operating/maintenance, and fuel costs, the levelized cost of generating exportable electricity in \$/kWh can be estimated. Here, a discount rate of 12% and an economic plant life of 25 years are assumed, corresponding to a capital recovery rate (CCR) of 12.8% per year.[11] The levelized cost of electricity (LCOE) in $\$/kWh_{ex}$, where kWh_{ex} is an exported unit of electricity, is:

$$LCOE = (ICC)*kW_e*CCR/E_{ex} + O\&M + F/E_{ex}$$

where ICC is the installed capital cost ($\$/kW_e$), kW_e is the installed capacity, E_{ex} is the number of kWh exported annually, O&M is the operating and maintenance cost (in $\$/kWh_{ex}$), and F is the annual fuel cost (in \$).

For the Sergio Gonzalez mill described above the estimated LCOE for the CEST and BIG/GT-CC systems would be:

$$LCOE_{S.G.,CEST} = 8402335/E_{ex} + 0.005 + [(82,620*P_{bag})+(118,422*P_{tsh})]/E_{ex}$$

$$LCOE_{S.G.,BIG/GT-CC} = 9983250/E_{ex} + 0.005 + [(82,620*P_{bag})+(118,422*P_{tsh})]/E_{ex}$$

where a capital cost of $\$1500/kW_e$ is assumed for the BIG/GT-CC. The value of E_{ex} will vary

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[9] Capital costs might be lower for equipment manufactured and/or installed in Cuba.

[10] This estimate includes the cost for the briquetting machine, assuming a 12% discount rate and a 15 year lifetime [7].

[11] The capital recovery rate is $i/[1 - (1+i)^{-N}]$, where i is the discoun: rate and N is the economic lifetime.

depending on the level of process steam required at the mill. Table A.3 gives total electricity generating costs for the existing and improved sugar mill steam demands, assuming $P_{bag} = 0$ and for varying values of the cost of trash, P_{tsh}.

Based on Table A.3, to achieve an electricity generating cost of $0.05/kWh, which is the price at which some Cuban sugar mills sell small amounts of surplus power to the grid during the milling season today [7], the cost to the cogenerator for delivered cane trash would need to be essentially zero in the CEST case, but could be as high as $50/dry tonne in the BIG/GT-CC case.

Potential all-Cuba electricity exports from sugar mills and oil import savings

The export electricity potential estimated above for the Sergio Gonzalez mill can be extrapolated to determine the approximate potential for Cuba-wide sugarcane-based electric power supply to the national grid, considering electricity exports from all sugar mills. Table A.4 shows the total cogeneration capacity that could be supported in the sugar industry and the potential annual electricity exports. Two sets of results are shown there. The higher capacity and export potential assume that the cogeneration facilities would be sized to consume all bagasse generated during the cane crushing season, and that sufficient other fuel would be available to operate for the full off-season. The second set of results assumes that the cogeneration facility size is reduced and that excess bagasse would be stored and used in the off-season to complement the use of trash. This second set of results is shown because of the estimate above that there would typically be insufficient trash to operate for the full off-season.

Interestingly, from the results for the trash-limited case, the total export electricity potential of the sugarcane industry in Cuba, assuming that $80x10^6$ tonnes of cane are crushed annually, is around 20,000 GWh/year with CEST technology and roughly double this for BIG/GT-CC technology. For comparison, utility power plants in Cuba generated around 16,000 GWh/year in the early 1990s, all from oil (Table A.5). Presently, however, electricity generation is running at 10,000 GWh/year due to shortages of fuel oil for the power plants [8]. Thus, from Cuba's sugarcane biomass-energy resource, the potential exists to produce about twice the electricty that is produced from oil in Cuba today by adopting CEST technology at sugar mills. With BIG/GT-CC systems, the potential exists to produce nearly quadruple the electricity generated from oil today.

If cane-generated electricity were to replace oil-fired electricity, there could be substantial savings to Cuba of oil import expenditures. For example, consider the following scenario. Cuba's electricity production in 2000 is 17,000 GWh/year, with a 5% per year increase thereafter, which would result in an electricity production of nearly 28,000 GWh/year in 2010. If all of the electricity requirement in 2000 were produced using oil, some 180 PJ of oil, or about $4x10^6$ tonnes[12] would be required, and oil consumption would increase 5% per year thereafter. If instead, all electricity that would otherwise have been generated from oil from 2000 to 2010 were to be generated from sugarcane biomass, the present value (in 1994) of the oil import savings, assuming a 12% discount rate, would be about $\$1.6x10^9$ for an oil price during the period 2000 to 2010 of $15/barrel ($110/tonne), which is close to the present world oil price. If the oil price were as high as $30/bbl ($220/tonne) during this period, the savings would be $\$3.2x10^9$. For a discount rate of 6%, the savings would be about double those for the 12% discount rate (Table A.6). For comparison, the most recent oil price projections of the U.S. Department of Energy are for a world crude oil price of $16 to $25 per barrel ($117-183/tonne) in 2000 and $21 to $36 per barrel ($154-264/tonne) in 2010 [10].

[12] Assuming a heat rate of 10.6 MJ/kWh and 45 GJ/tonne of oil.

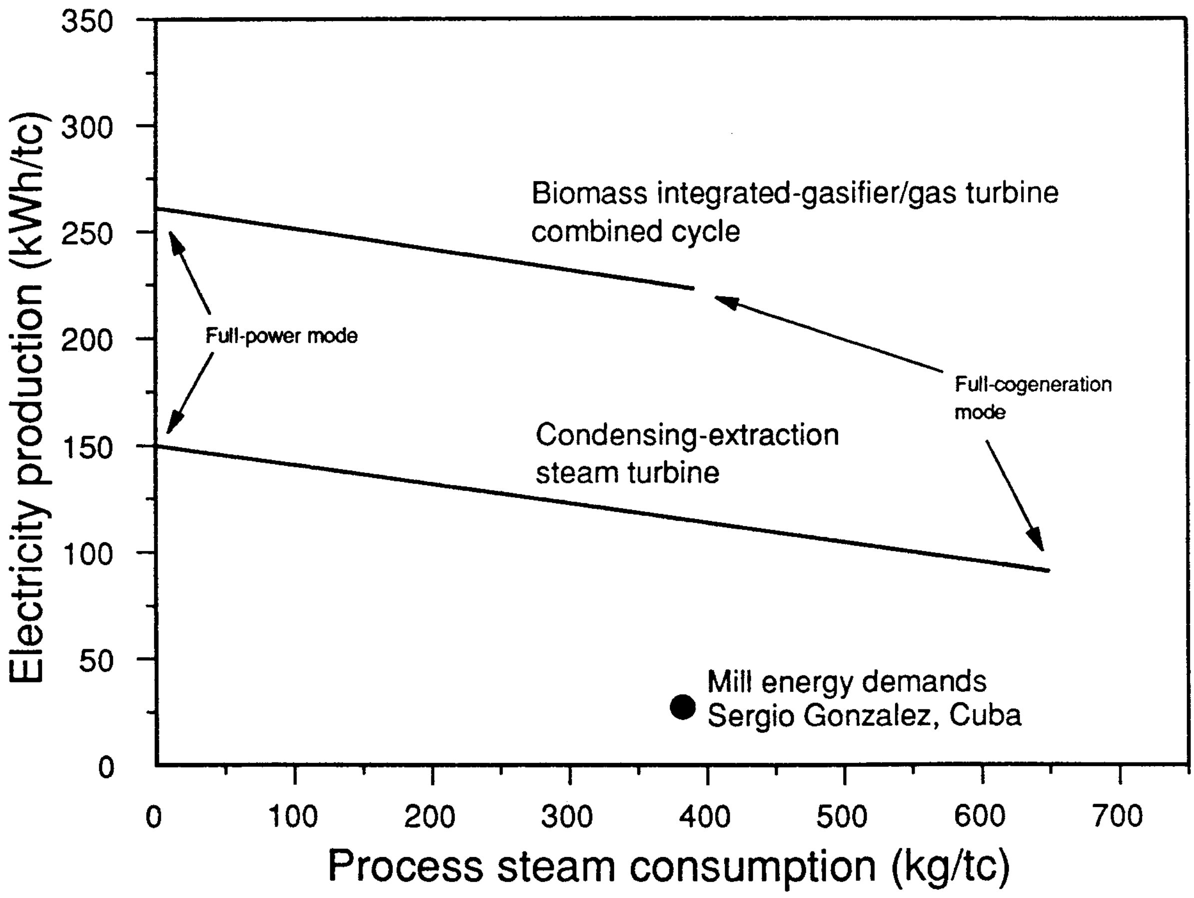
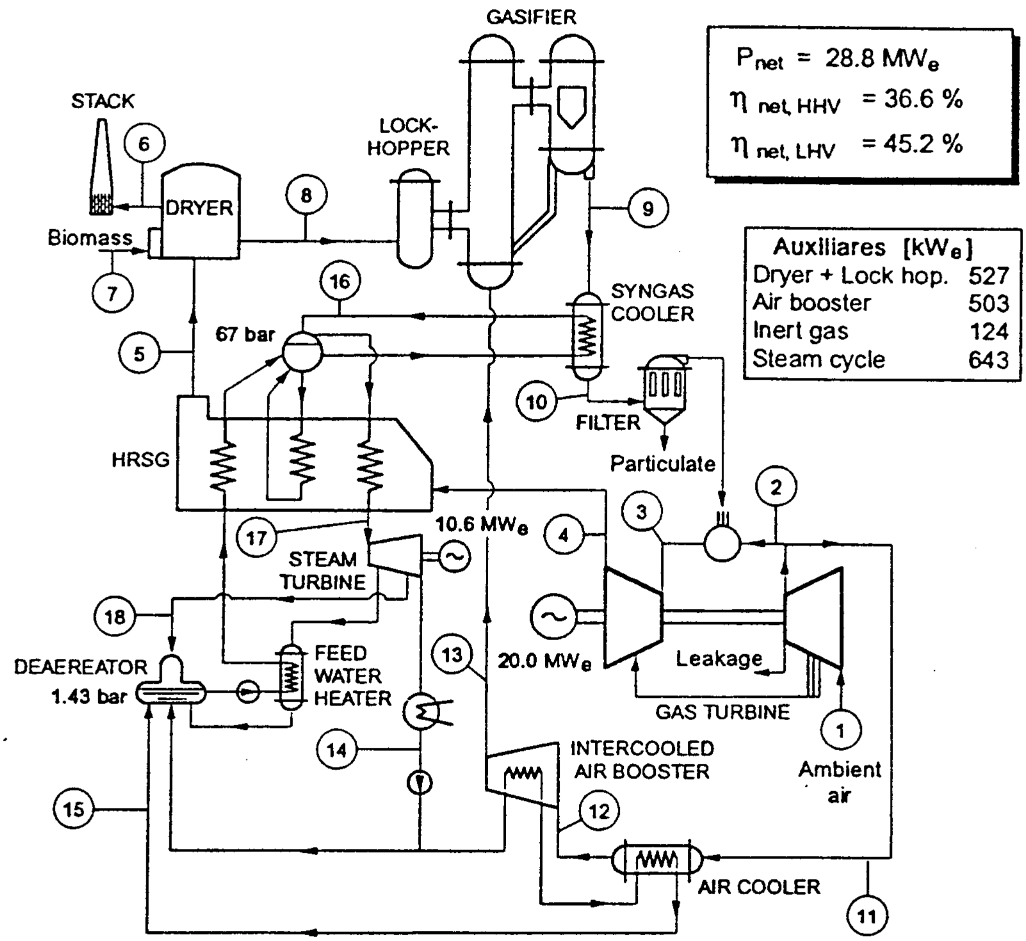


Figure A.1. Estimated cogeneration performance characteristics for two cogeneration technologies using sugarcane bagasse as fuel.



Point	1	2	3	4	5	6	7	8	9
T, °C	15	457	1147	472	210	93	15	70	953
P, bar	1.013	19.4	18.8	1.07	1.04	1.013	1.013	1.013	28.6
m, kg/s	68.0	50.7	62.9	72.4	72.4	75.6	7.86	4.62	12.2

Point	10	11	12	13	14	15	16	17	18
T, °C	350	457	60	99	35	120	283	443	110
P, bar	28.0	19.4	19.0	30.4	0.056	4.80	67.0	60.3	1.43
m, kg/s	12.2	7.24	7.24	7.24	11.0	8.87	6.96	12.0	0.10

Figure A.2. Estimated energy and mass balances, from [5], for biomass-gasifier/gas turbine combined cycle (BIG/GT-CC) technology that is under development for possible commercial-scale demonstration in Brazil [4]. The fuel in the case shown here is wood chips with 50% moisture content and a higher heating value of 20 GJ/tonne.

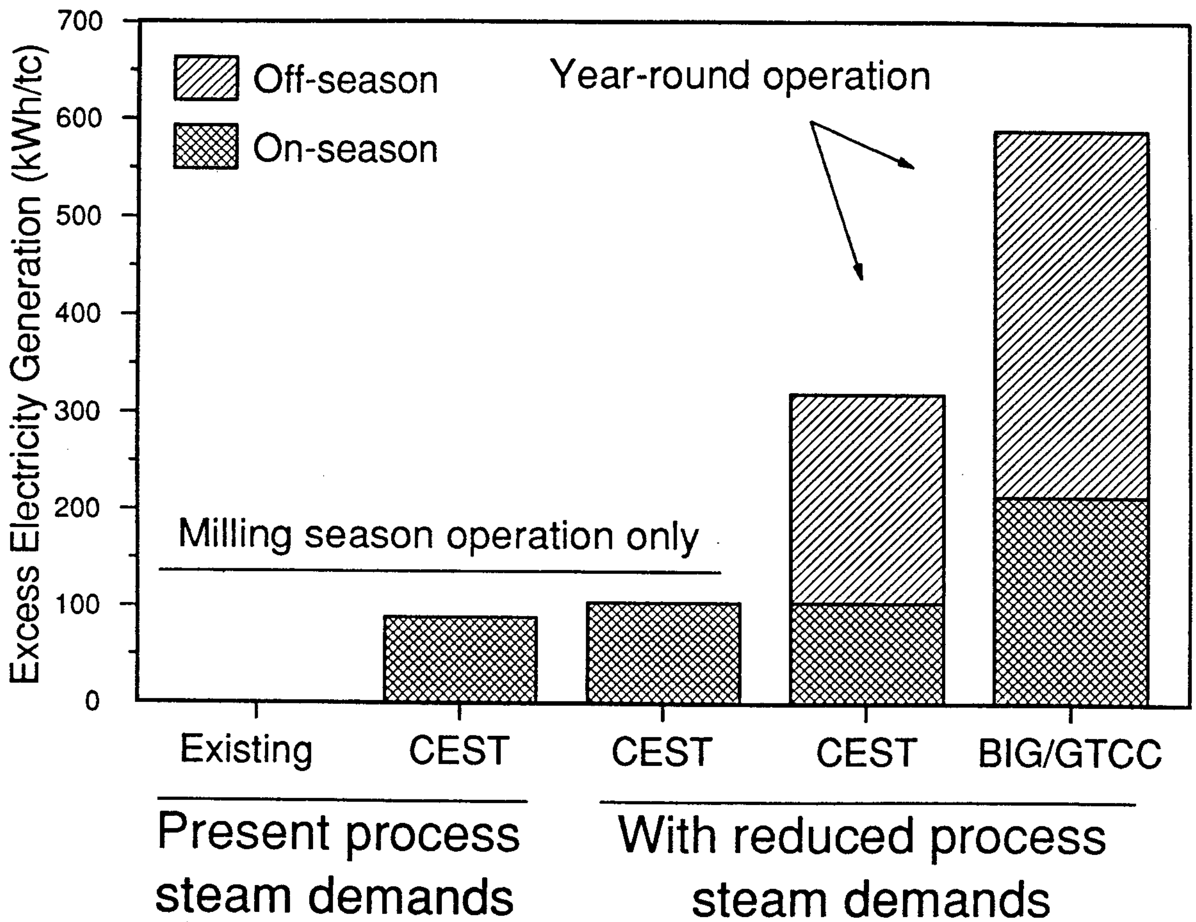


Figure A.3. Summary of electricity export potential from sugar factories in Cuba for alternative cogeneration technologies.

Table A.1. Estimated potential electricity generating in excess of on-site needs at the Sergio Gonzalez mill, assuming either CEST or BIG/GT-CC technology at the mill with either the "present" or "improved" energy demand profiles.

Cogeneration technology →	CEST		BIG/GT-CC	
Mill energy demands →	Present	Improved	Present	Improved
Installed capacity (MW_e)[a]	30.0		52.2	
Electricity exports during milling season (kWh/tc)[b]	88	104	197	214
Electricity exports during off-season (kWh/tc)[c]	215	215	374	374
TOTAL ELECTRICITY EXPORTS (kWh/tc)	303	319	571	588
Annual electricity production (GWh/year)[d]	185	195	349	360

(a) Calculated based on the full-power mode (left end points in Fig. A.1).
For CEST, MW_e = (150 kWh/tc)*(4800 tc/day)/(24 h/d)

(b) These are the electricity productions shown in Fig. A.1, from which 27 kWh/tc have been subtracted to account for mill electricity demands. The equations describing the lines in Fig. A.1 are as follows:
$(kWh/tc)_{CEST}$ = 150 - 0.0909*(kg_s/tc), where kg_s/tc is the steam demand per tonne of cane.
$(kWh/tc)_{BIG/GT-CC}$ = 261 - 0.0972*(kg_s/tc)

(c) This is normalized to the cane production during the milling season. The off-season electricity production is calculated as the full-power mode production augmented by the additional operating time available for operating during the off-season. Thus, for CEST, $(kWh/tc)_{off-season}$ = (150 kWh/tc)*(215*0.85/150*0.85), and for BIG/GT-CC, $(kWh/tc)_{off-season}$ = (261 kWh/tc)*(215*0.85/150*0.85).

(d) Calculated as (kWh/tc)*(tc/year), assuming 4800 tc/day, 150 day season, and 85% capacity factor.

Table A.2. National sugarcane biomass balance for Cuba, based on production of 8 million tonnes of raw sugar [11].

	Mass (10^3 tonnes)	
	Bare Cane Stalks	Residues
PRE-HARVEST, IN THE FIELD	77,907.6[a]	25,969.1[b]
Machine Harvested	**55,314.4**	**18,438.1**
Left in field after harvest	3,042.3[c]	9,219.5
Diverted for seed	1,380.0	243.4
Losses in transport to cleaning station	522.7	92.2
Left at the cleaning station	522.7	4,425.2
Losses in transport to the mills	498.5	44.6
Delivered to the mill gate[d]	49,348.2[e]	4,413.7[f]
Manually Harvested	**22,593.2**	**7,531.0**
Left in field after harvest	424.3[c]	3,558.5
Diverted for seed	1,380.0	414.0
Losses in transport to cleaning station	207.9	35.6
Left at the cleaning station	370.5	2,219.4
Losses in transport to the mills	202.1	13.0
Delivered to the mill gate[d]	20,008.5[e]	1,290.4[f]

(a) Moisture content is as cut.

(b) This consists of 9,868,400 tonnes of dry leaves, 9,398,900 tonnes of green leaves, 5,193,800 tonnes of green tops, and 1,508,000 tonnes of dried (dead) cane stalks. The total dry matter in the sum of these residues is 13,452,000 tonnes, with a lower heating value of 16 GJ/dry tonne.

(c) These are harvesting losses.

(d) The sum of the cane and residues at the mill gate correspond to the total biomass that passes through the crushing mills.

(e) The average bagasse content in this cane is 125 dry kg per tonne of cane.

(f) These residues are in addition to the bagasse (see previous note) that is extracted during milling.

Table A.3. Estimated levelized cost of generating exportable electricity from a sugar mill cogeneration facility in Cuba as a function of the assumed cost of recovering and delivering trash to the facility as an off-season fuel.

Cogeneration technology →		CEST		BIG/GT-CC	
Sugar mill energy demands →		Present	Improved	Present	Improved
Cost of trash delivered to cogenerator ↓		Levelized Cost of Exported Electricity ($/kWh$_{ex}$)			
P_{tsh} ($/dry tonne)	$/GJ				
0	0	0.050	0.048	0.034	0.033
10	0.53	0.057	0.054	0.037	0.036
20	1.05	0.063	0.060	0.040	0.039
30	1.58	0.070	0.066	0.044	0.043
40	2.11	0.076	0.072	0.047	0.046
50	2.63	0.082	0.078	0.051	0.049
60	3.16	0.089	0.085	0.054	0.052

Table A.4. Estimated all-Cuba electricity generating potential in excess of sugar industry electricity requirements, assuming either CEST or BIG/GT-CC technology at the mill with either the "present" or "improved" energy demand profiles for sugar factories.

Cogeneration technology →	CEST		BIG/GT-CC	
Mill energy demands →	Present	Improved	Present	Improved
Assumed Cuba sugarcane production (tonnes)	80,000,000			
Total capacity that could be supported (MW_e)[a]	3,333		5,800	
Annual electricity production (GWh/year)[b]	24,240	25,520	45,680	47,040
With trash limiting the installed capacity and annual electricity generation[c]				
Total capacity (MW_e)	2,790		4,855	
Annual electricity production (GWh/year)	20,292	21,364	38,241	39,379

(a) Calculated assuming that the bagasse available at a mill with a capacity of 4800 tc/day would support 30.0 MW_e of CEST or 52.2 MW_e of BIG/GT-CC (see Table A.1).

(b) Assuming the total kWh/tc export levels shown in Table A.1, which assumes that sufficient fuel is available to operate during the full off-season at rated capacity.

(c) Based on Table A.2, and as discussed in the text, it appears that the trash production associated with sugarcane today in Cuba would be insufficient to operate cogeneration facilities for the full off-season, if the facilities are sized to utilize all bagasse that is available during the crushing season.

Alternatively, the cogeneration facility could be downsized so that excess bagasse accumulates during the crushing season and can supplement trash as a fuel during the off-season. The percentage reductions in capacity and electricity generation are calculated as follows. If the total amount of biomass associated with each tonne of cane delivered to the mills is 135 dry kg of bagasse and 140 dry kg of trash (see text discussion), and these fuels have the same heating values, then the total biomass fuel available annually, assuming 80×10^6 tonnes of cane produced would be $(80,000,000)*(135+140) = 22 \times 10^9$ dry kg. If the use of this fuel at a cogeneration facility operating with an 85% annual capacity factor is to be equally distributed throughout the year, the daily fuel consumption would be $(22 \times 10^6)/(365*0.85) = 70,911$ tonnes/day. For comparison, during the milling season the dry tonnage of bagasse that would be available daily is (80,000,000 tc)*(0.135 t_d/tc)/(150*0.85) = 84,706 tonnes/day. Thus, the cogeneration facility must be derated by 100*(84706-70911)/84706 = 16%.

Table A.5. Electricity generation from oil in Cuba.[a]

Year	Production (GWh)
1985	12,200
1986	13,200
1987	13,600
1988	14,500
1989	15,200
1990	16,200
1991	16,300
1992	
1993	

(a) From [9]. The 1990 and 1991 figures are indicated to be United Nations' estimates.

Table A.6. Present value (1994) of oil import savings for Cuba, 2000-2010, as a function of the levelized oil import price, assuming that all oil-generated electricity is replaced by electricity generated from sugarcane bagasse and trash.

Discount rate (%/year)	Levelized crude oil price, \$/barrel (\$/tonne)[b]				
	15 (110)	20 (147)	25 (183)	30 (220)	35 (257)
	Oil import savings, 2000-2010 (10^6 dollars in 1994)[a]				
6.0	2,945	3,936	4,900	5,890	6,882
12.0	1,590	2,125	2,645	3,180	3,715

(a) If oil were to be used to produce 17,000 GWh of electricity in 2000, the oil requirement would be 4×10^6 tonnes, with an associated cost (10^6 \$) of $4*P_o$, where P_o is the cost of oil in \$/tonne. If oil consumption were to increase at at some rate, r, (due to assumed r rate of increase in electricity generation), the year-2000 value of all oil expenditures from 2000 to 2010, OE (in 10^6 \$), would be $(4*P_o)*(1 - [1+d]^{-N})/d$, where $d = (i - r)/(1 + r)$, i is the assumed discount rate, and N is 10 years. The present value (10^6 \$ in 1994) of OE is then $OE/(1 + i)^6$.

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