Energy Aspects of Fiji's Sugar Industry: A Case for More Efficient Electricity Generation from Bagasse

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Abstract

Bagasse, a by-product of sugar cane crushing, is the major energy source for the sugar mills in Fiji. In 2001, the FSC utilized some 700,000 tonnes of wet bagasse, generating an average of 25 MW of electrical power during the crushing season. This paper proposes that there is enough bagasse to generate all the required electricity for the FSC and to also sell the excess to other users, or to the national power company. Currently, not all the bagasse is used and of the amount that is used, the overall conversion efficiency is relatively low. This paper makes a case for improving the efficiency of generating and using electricity from bagasse. By doing so, FSC can greatly increase its energy position in the long-term.

Introduction

Sugar remains one of the largest revenue earners for Fiji, bringing in over $F200m as export revenue annually. Export of sugar produced from sugar cane is one of the two major export revenue earners for Fiji, the other being garments. Since the 1930's and until early 1980's, sugar was the biggest export earner, earning around 70% of the country's total export income. Around 77,000 hectares of land is under sugarcane cultivation, with over 22,500 people directly involved in cane cultivation, and another twenty four thousand in the harvesting, transportation and milling processes. The industry absorbs a large section of the workforce in various forms.

The four sugar mills in Fiji produce over 200,000 tonnes of sugar, and between 130,000 and 190,000 tonnes of molasses, from upto 4 million tonnes of sugar cane (Narayan and Prasad, 2003; FSC Annual Report, 2001; Reddy, 2003).

In recent years, the production of sugar has declined quite significantly due to several reasons, the major one being the uncertainty over, and the non-renewal of a substantial number of leases. Total sugar produced in 2001 was merely 293,133 tonnes, from 2.8 million tonnes of sugarcane, a decline of some 26% from the previous year (FSC, 2001). Sugar production was at its peak in the 1980's, with a record sugar production of over 500,000 tonnes in 1986. The average sugarcane yield is around 42 tonnes of cane per hectare. Sugarcane is grown mostly on individual farms, which range in size from a few hectares to several hundred hectares, with an average farm size of 3.4 hectares. The sugarcane output varies considerably, depending on several major factors that include the size of the farm, the quality of the land, the variety of cane used, rainfall and the amount of effort and fertilizer put into the farms.

Cane is milled by the Fiji Sugar Corporation Limited, a company with a majority government shareholding. Farmers and the miller share the proceeds of sugar sales on a basis specified in a contract between the growers and the farmers. The miller's share of the proceeds is the gross income for the miller, from which it has to fund its operations and investments, and produce a dividend for the shareholders.

Energy used in the mills for sugar and molasses production is a cost item for the miller. The energy comes mainly from bagasse, with external energy coming from the Fiji Electricity Authority, the company that generates, transmits and sells electricity in Fiji. Energy production by FSC, however, is rather inefficient, with an average overall efficiency (bagasse to electricity) of between 5 and 8%.

This paper examines the energy aspects of the sugar mills and makes a case for greater efficiency in the energy generation processes, from the steam boilers to the generators. Using bagasse more energy-efficiently will ensure that more energy is generated, from which any excess could be sold to the national grid. This can be done by using steam of higher quality as well as by utilizing a different technology to that presently employed.

Economic and financial aspects of the proposed power generation are beyond the scope of this paper and beyond the expertise of the author. However, a simple economic analysis is done to give an idea of the range of energy cost from the proposed increase in the efficiency of the power conversion systems from the mills.

A major constraint to this paper is that energy data has not been publicly available for the years after 1992. Several attempts to get more recent data from the FSC were made, but these proved futile.[1]

The Case for Using Bagasse, A Form of Renewable Energy

Bagasse, the waste product of the cane crushing and sugar producing process, is a form of biomass. Used sustainably it is a form of renewable energy (RE). Since the carbon dioxide that is produced by burning bagasse is taken up by plants, there is minimal impact on the environment, in terms of contribution to the greenhouse gas (GHG) emission (Walter and Overend, 1998). While renewable energy sources such as biomass, hydro and wind make a significant contribution to the total global energy used, there is significant scope for increasing this a great deal more, particularly in the area of electricity generation. In Fiji, the major RE resource-based power generation includes hydro-electric power and biomass energy systems.

It is worthwhile to consider some of the major factors that support the arguments for increasing the contribution of energy from RE sources (Prasad, 1988). For biomass energy (which includes bagasse as a waste product) in particular, these include the following:

- Biomass energy sources have richness and diversity and can supply most, if not all, energy needs
- Biomass sources lead to small, large or massive power system sizes
- The modular construction of biomass power systems allows

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[1] It is somewhat unfortunate that the energy aspect of the sugar industry is not given the importance and prominence that it deserves. This is clearly reflected in the annual reports of the FSC where there is no mention of energy statistics or any reporting on energy use, energy data, efficiencies or energy options. Yet energy is a vital ingredient in the sugar industry and has enormous potential for not only cost saving, but generating additional revenue for the FSC.

for economical expansion

- Power generation using biomass sources can be established rapidly and can grow quickly
- No breakthrough is required for mass commercial use, for example using combustion, gasification or other conversion processes
- Biomass energy systems give rise to energy independence, due to fairly equitable global distribution of RE sources
- Energy costs for biomass-based power systems are decreasing, while that for fossil fuel-based systems are increasing, if full allowance is made for the cost of minimizing environmental damage
- Biomass energy systems do not affect overall environmental energy balance
- Many combinations of biomass power systems with fossil fuel sources are possible
- Many biomass-based power systems have passed beyond the small scale and experimental stages and have already been commercialized

For Fiji, the major renewable energy options include hydro power (which is already utilized to the extent of over 100 MW of installed capacity), biomass (for cooking, industrial applications and power generation) and solar power (for water heating).[2] The potential for wind power, in selected and suitable sites, is significant. The Fiji Electricity Authority (FEA) is now considering a 1 MW wind power system for the future.

Efficient use of bagasse can make a significant contribution to total electricity generation in the country. It will be shown, in a later section, that by using the technology of bagasse gasification, combined with a gas turbine system and a second conventional steam turbine system, the FSC can realize a 60 MW power generation system which can operate year-round (with the use of additional fuel in the form of woody biomass or coal) and generate some 428 GWh of electricity, which is over 90% of the total electricity presently generated by the FEA. So far, this has not been done because the FSC simply

[2] See Appendix to this paper for basic energy units.

generates all the energy that it requires for the mills during the crushing season using whatever bagasse is required; it is, simply, not concerned about generating electricity for sale to the utility provider on a commercial basis. As will be shown in later sections, the potential to do this exists. Greater efficiency implies generally lower greenhouse gas emission. This is an added incentive to the economic one. In addition, the bagasse that remains after the end of the crushing season can be converted to fertilizer which can be sold to the farmers at an economic cost.

A Brief Overview of Bagasse Gasification Power Systems

Bagasse gasification power systems are now being widely looked at as a major energy source. We review the progress made in some other countries on the use of biomass, including bagasse, for generation of power. In particular, the focus will be on the use of gas produced from the gasification of bagasse from sugar mills and the use of gas turbines, combined with a steam power system, to convert the fuel gas into electricity and process steam.

The European Union

Following its commitment to the Kyoto Protocol, the European Union is putting a huge effort on significantly increasing the energy use from biomass resources (Grassi, 1998; de Lange and Barbucci, 1998; Hillring, 1998). Bioenergy is set to contribute some 44 MTOE per year, which is approximately 3% of the total energy used in Europe. For power generation, the projected electricity output from biomass is 230 TWh per year, equivalent to 135 MTOE. Of the 35 power generation units being planned or already commissioned, 15 are designed for fluidized bed combustion of bagasse, yielding 1500 MW of electricity. As far as the power market goes, the EU states that `power generation from biomass is the most promising future large-scale market for the EU' (Grassi, 1998: 987).

There are three major technologies being considered or actually used for biomass energy conversion to heat, electricity and biofuels. These are:

- Fluidised bed combustion

- Atmospheric gasification with a combined cycle power plant
- Bio-crude oil/gasoil/ diesel (25%)

The actual and projected cost for power generation ranges between 6 to 7 Euro cents per kWh, for all of these technologies.

The projected increases in employment numbers as a result of these initiatives in the biomass-based heat, power, chemicals and the transportation areas are around 2 million new jobs in the next five years.

The Brazilian Experience

Brazil has been a world leader in the production of ethanol from sugar and cassava. Through PROALCOOL, its national alcohol programme, it has been producing large amounts of ethanol for transportation. However, electricity production from the private sector has been less than encouraging; only 6% of the total production has come from the private sector. The two major reasons have been put down to economic and political barriers (Coelho and Bolognini, 1998).

There is great potential for power generation from the sugar sector. During the 1996/97 sugarcane harvesting season, 273 million tones of cane was crushed, resulting in the production of 13.5 million tones of sugar and 13.7 billion litres of ethanol. There is thus a huge potential for power generation using a variety of technologies, including gasification of bagasse. The major difficulty is that the utility compaies offer a relatively low price for biomass generated electricity. This is one of the reasons why in 1995, only 96 GWh of electricity was bought by the Sao Paulo utility companies, compared to the 80,000 GWh consumed (Coelho and Bolognini, 1998).

The Indian Efforts

In India, New and Renewable Energy Sources (NRES), the key central government organization charged with the responsibility of research and development in renewable energy, has favoured bagasse-based cogeneration of electricity as one of the technologies that has great promise (Sharma and Sharma, 1998). From the 428 sugar mills, there is a potential surplus power of some 3.5 GW. The main problems have been financial, transmission losses and discouragement by established power industries.

Incentive schemes by the government have been initiated to encourage the realization of the huge potential to generate heat and electricity from biomass resources, particularly bagasse from sugar mills. One key factor is that bagasse is available only during the harvesting season, which is some 6-7 months. For continuous power generation, some other fuel, such as wood or coal, will have to be used. While there is an economic potential of 421 MW, with marginal investment some 1500 MW of electricity production could be easily realized.

The three major technologies being considered are:

- Extraction back pressure steam turbine-based power system
- Extraction condensing steam turbine power system
- Dual-fuel power generation, using gasification as a possible route

Aspects of Fiji's Sugar Milling and Energy Operations

The energy aspects of the sugar mills, in the form of fuel used, and energy produced, consumed and sold, are shown in Table 1.

Table 1: Energy Generation and Use: the Fiji Sugar Mills

Year	Diesel Gen. Cap kW	Steam Gen. Cap. KW	Total Gen. Cap. kW	Elect Gen. (Diesel) MWh	Elect Gen. (Steam) MWh	Total Elect. Gen. MWh	Electricity Purchased MWh	Electricity Sold MWh	Total Used MWh
1981	3730	20200	23930	1572	50292	51864	939	5079	47724
1982	2900	23200	26100	3745	54893	58638	8077	3029	63686
1983	2700	28200	30900	4707	28892	33599	7247	3328	37518
1984	2700	28200	30900	645	47716	48361	5852	1796	52417
1985	2700	28200	30900	428	40138	40566	6343	2764	44145
1986	2700	28200	30900	224	46891	47115	6714	2975	50854
1987	2700	28200	30900	156	39702	39858	6784	2454	44188
1988	2480	25700	28180	245	34233	34478	12038	1636	44880
1989	2480	25700	28180	322	49655	49977	6696	3020	53653
1990	2480	25700	28180	374	46923	47297	13943	3175	58065
1991	3964	24500	28464	158	42175	42333	10334	2802	49865
1992	3964	24500	28464	338	43823	44161	11524	3538	52147
Avg	2958	25875	28833	1076	43778	44854	8041	2966	49929

(Source: FSC Annual Reports)

The period covered is 1981-1992. Unfortunately, data for the years beyond 1992 has not been made available by FSC either publicly through its annual reports or other publications, or to the author despite personal requests for this. For the period 1985-94, average cane crushed annually was 3.6 million tonnes, from which 425,000 tonnes of sugar and 140,000 tonnes of molasses was produced. Electricity produced by burning bagasse was 44 GWh. Table 2 provides some sugar production and bagasse data in terms of their percentage constituents. It is noted that moisture dominates sugar cane, averaging 72.5% of its mass. Also noteworthy is the statistic that about 2.5% of the cane is classed as `impurities'.

Table 2: Sugar and Bagasse Data

Cane constituent	%	Products and by-products	%
Fibre	12.5	Sugar	11.0
Sucrose	12.5	Molasses	4.5
Impurities	2.5	Bagasse (50% mcwb)	25.0
Water	72.5	Water	59.0
Total	100	Mill mud	0.5

(Source: Reddy, 2003)

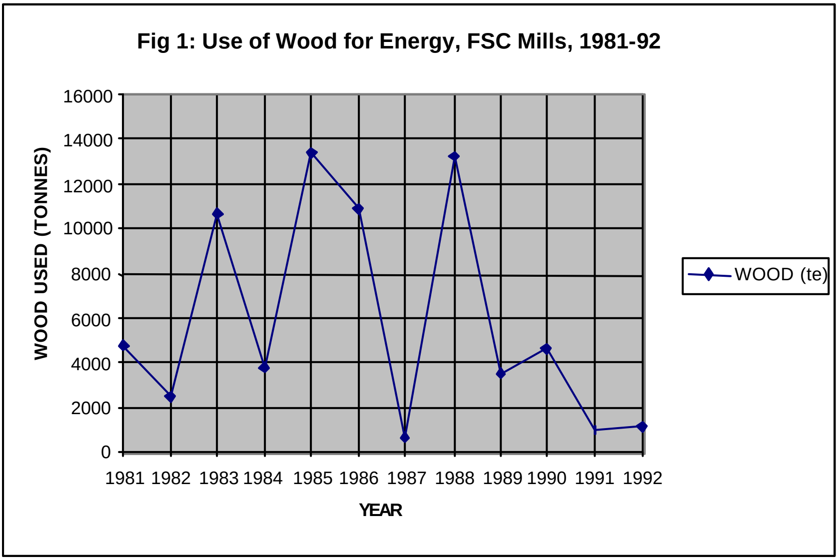
Some general power generation aspects of the sugar mills are listed in Table 3. The total installed capacity is almost 48 MW, of which the total steam capacity (bagasse) is 40.5 MW. An average of some 7 MW of power was exported to the FEA grid in 2001.

Table 3: Current Power Generation Data for the FSC Sugar Mills

Mill	Installed Capacity (MW)	Power Exported (season average) MW	Internal Use (MW)
Lautoka	17 Steam 2 Diesel	4	4.5-5.0
Rarawai	5.75 Steam 2.4 Diesel	--	3.8-4.2
Labasa	14 steam 2 diesel	3	3.8-4.2
Penang	3.75 Steam 1 Diesel	--	1.6-1.8
Total	40.5 Steam 7.4 Diesel	7	13.7-15.2

(Source: Reddy, 2003)

The sugar mills use some wood to meet their energy requirements. Although the amounts used are not large and vary significantly from season to season, this does represent energy levels ranging from 8 TJ to 216 TJ per season (taking an energy value of 20 GJ/te and assuming a moisture content of 20% on a wet basis). Figure 1 shows wood use by the sugar mills from 1981 to 1992.



Use of Bagasse for Steam and Power Generation

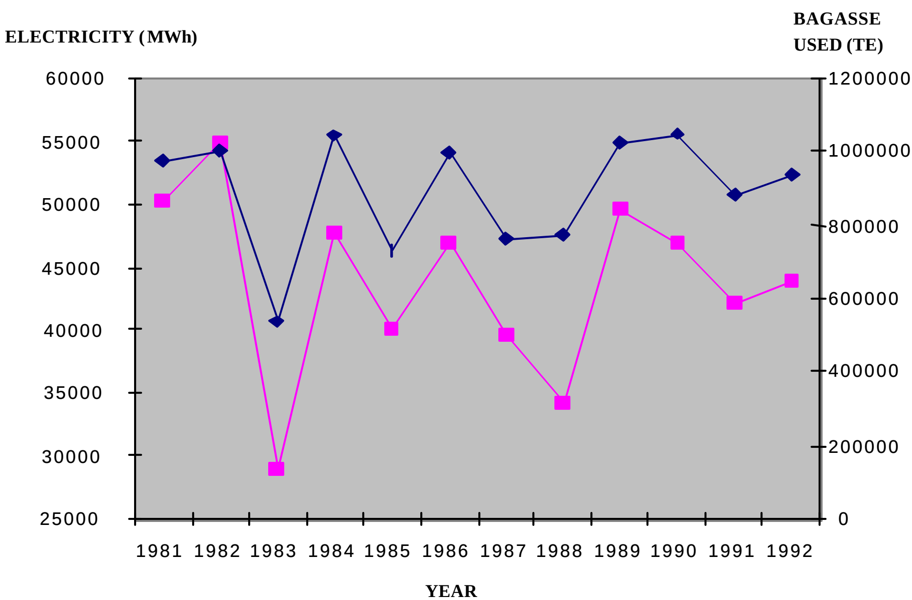
At the very outset, it is acknowledged that there are a huge number of variables when dealing with the complex subject of energy flows and conversion efficiencies that apply within a sugar mill. Therefore, when modeling the energy supply and conversion system inside a sugar mill, one has to make many assumptions and to keep many variables at certain, constant levels. Some of the more obvious variables that apply within the energy conversion process include:

- The energy sources (bagasse, woody biomass, purchased electricity, fuel oil, coal, etc.)
- The number, ratings, age and history of the several boilers used

- The age and performance of the various equipment that use energy in various forms
- The pressure, temperature and mass flow of steam to the various equipment
- The amount of energy needed to process the varying input of cane
- The varying load on the boilers and the generators
- The quality and amount of sugarcane brought to the mills
- The moisture levels of the bagasse produced
- The content of fibre, ash and moisture in the sugarcane itself from the different areas
- The energy wastage due to mill stoppages, varying mill load and mill efficiencies

Figure 2 shows the amount of electricity generated and bagasse used for the period 1981-92.

Figure 2: Electricity from Bagasse, FSC



Getting More Power by Improving Efficiency

In this section we consider the effect of using more efficient cycles to extract energy from the combustion of bagasse. This necessitates a brief consideration of basic thermodynamics and of the fundamentals of the Rankine and the Brayton cycles[3].

A Brief Look at Thermodynamic Cycles

The production of mechanical power (sometimes referred to as shaft power) from heat engines or turbines is based upon thermodynamic cycles. That is, a working fluid (liquid or gas) is taken through a cycle, through the addition or extraction of thermal (heat) energy, and the extraction or addition of work. Work is defined as the amount of useful energy obtained from each cycle. It usually refers to the energy put into a cycle from a compressor, for example, or the amount of energy taken out, as shaft power. The petrol or gasoline engine, for example, works by burning fuel (petrol) briefly inside a closed space (the cylinder); the combustion products (the hot gases at high temperature) then push against a piston, creating work; the gases are then exhausted and a fresh supply of fuel and air is then taken into the cylinder for the next cycle. There are thus four strokes or paths for this cycle: the intake (fuel and air entry); the fuel combustion (heat production stroke); the working stroke (production of useful mechanical power) and the exhaust of the combustion products (heat losing stroke), in this case, into the atmosphere. The total power developed by the engine is (approximately) the work output per cycle multiplied by the number of cycles that occur per second.

The mechanical power output is converted into electricity by the use of generators or alternators. Some of the more practical thermodynamic cycles include Otto (petrol engine), Diesel (diesel engine), Rankine (steam engine or turbine), Stirling (hot air engine) and Brayton (gas turbine) cycles.

[3] The discussion on the thermodynamic cycles is to aid non-technical readers; others can skip the following 3 sub-sections.

The Rankine Cycle (Steam Engine/Turbine Cycle)

For this cycle, steam is the working fluid. The components of the cycle include the following:

- Water is pumped to a high pressure inside the boiler and is converted into steam at high pressure and temperature by the addition of heat
- The steam expands against a piston in a cylinder, producing mechanical work
- The steam, its energy almost spent, is exhausted into a condenser
- The exhaust steam is condensed into water and is ready to be pumped back into the boiler, thus completing one cycle of operations.

The work done during the steam expansion is the difference between the enthalpy (or, crudely, the heat energy content of the steam) as it is allowed to expand from its initial high pressure and temperature, to that at the beginning of the exhaust process, as the wet steam is discharged into a condenser, at a lower pressure and temperature. The net work per cycle is the difference between the work produced by the steam as it expands (during the working stroke) and the work put in externally to pump the water into the boiler. The higher the pressure and temperature of the steam in the boiler, the higher is the power output.

The Brayton Cycle (Gas Turbine Cycle)

The Brayton Cycle is the basis of the operation of gas turbines (such as the ones used to power jet engines). There are several variants of the cycle (like the open, closed, single-stage, and 2-stage ones). The working fluid in this case is a gas at high pressure and temperature. The basic (open) cycle consists of the following:

- The working fluid is introduced into the turbine (it can be produced either through internal or external combustion, or a supply of gas is heated by some energy source, such as solar energy)

- The gas (initially at very high pressure and temperature) is allowed to expand inside the turbine blades, losing energy and producing work
- The spent working fluid is discharged
- A fresh amount of working fluid is compressed (external work is required) to a high pressure and temperature, ready for the next cycle.

The work done per cycle and the net work are calculated, as for the Rankine cycle, by similar means. The efficiency of the Brayton cycle depends essentially on the temperatures at which the working fluid are introduced and exhausted and the compression ratio. Depending on the pressure and temperatures used, a Brayton cycle is inherently more efficient than the Rankine cycle for steam turbines. The other major advantage of using a gas turbine is that the gas discharged from the turbine has enough energy for a steam cycle to operate off its heat. This configuration is the so-called Combined Cycle approach to generate greater power.

As water is heated, it turns to steam. At a constant pressure, as more and more heat is added to the water, it turns to steam and the temperature remains constant until all of the water is converted into vapour. With further addition of heat, the temperature of the steam rises further (at the same pressure) and it becomes superheated, having with it a greater amount of heat or enthalpy. The degree of superheat of the steam thus produced is equal to the final temperature achieved and the constant temperature at which the water is converted wholly into steam. Steam quality refers to the amount of water that a given supply of steam contains; superheated steam, by definition, has no water at all.

Getting More Power at FSC

The existing steam supply and power generation at the sugar mills in Fiji are at relatively low pressure (1.84 M Pa or 18.2 bars) and temperature (260^{C}). However, some of the newer boilers operate at higher pressures and temperatures (30 bars and 300^{C}) (Koers, private communication). From tables of the properties of steam, the energy content of steam for these conditions is 3024 kJ per kilogram. If a higher pressure and degree of superheat of steam were to be used, the enthalpy would be greater. If, for example, steam at a pressure and temperature of 8 M Pa (79 bars) and 500^{C} (205 degree of superheat) respectively were to be used, the enthalpy of the steam would be 3400 kJ per kilogram, an increase of 12% in enthalpy. The latter condition of steam would lead to a higher work output. For the ideal, isentropic steam expansion, there is an increase of 36% in the net work produced by steam, which is quite a significant amount. Obviously, there has to be additional expenditure in ensuring the power system is capable of handling these higher pressure and temperatures.

Modern boilers of medium size (over the 10 MW thermal output) are capable of high efficiencies of between 70-80%, depending on the fuel used, boiler design and operational characteristics. For biomass-fuelled boilers, using bagasse and wood wastes such as sawdust and woodchips, the efficiency depends strongly on the moisture content of the fuel. Experiments on a small-scale sawdust-fired boiler, for example, have shown that boiler efficiencies can reach up to 70% efficiency under optimum conditions (Prasad, 1988).

The use of a gas turbine/steam turbine in the combined cycle power generation operation yields overall efficiencies (electrical energy output to the fuel energy input) of over 20%, for medium-scale systems for biomass-based fuels (Hagen and Kaneff, 1990). The gasification of bagasse, using a number of technologies available, can yield high output energy in the form of high temperature and pressure gaseous fuel, which can then, after appropriate cleaning, drive a gas turbine. The exhaust output from the gas turbine can then drive a conventional boiler which feeds a steam turbine. The combined efficiency of such a gas/steam system has the potential for much higher efficiencies than a steam turbine system only. Such efficiencies have actually been realised. Solar gasification of bagasse is yet another technology that has been advocated (Hagen and Kaneff, 1990), with the added advantage of lower carbon dioxide emission. Efficient combustion of bagasse also ensures less pollution, as the more efficient the combustion process, the lower is the amount of particulate matter and carbon monoxide pollution.[4]

[4] A major problem in the sugar towns (Lautoka, Ba, Rakiraki and Labasa), is particle pollution. The problem could have health consequences. More efficient energy producing technology could significantly reduce this problem.

For the purpose of determining the energy (both thermal and electricity) available from the existing and the proposed generation technology, certain assumptions have been made and various operating parameters have been taken. Some of these, wherever possible, correspond to the operating conditions in the Fiji sugar mills. However, where such data has not been available or readily forthcoming, assumptions, based on actual and similar systems operating elsewhere, have been made. Such data includes the efficiencies of various components, such as the boiler(s), gas turbine, steam turbine, condenser pressure, energy value of bagasse, steam pressures and temperatures and the amount of steam energy, as a fraction of the total energy requirements for the mill.

Currently, the sugar mills generate steam and electricity relatively inefficiently, given the low pressure (1.84 M Pa) and relatively low temperature (260^{C}) of the steam generated by the bagasse-fired boiler. For these values, and using a condenser at vacuum pressures, the ideal, isentropic efficiency of the Rankine cycle is around 25%. The use of higher pressures (say 8 M Pa) and temperatures (say 500^{C}) leads to a higher ideal efficiency of around 45%.

The overall power generation efficiency (annual electrical output divided by the gross heating value of the total annual bagasse used) is quite low, at between 3-7%. With the cogeneration of both steam and electricity, the overall conversion efficiency is greatly increased, but is still nowhere close to its true potential.

Using steam at 8 MPa pressure and at 500^{C} temperature, the levels of power generation theoretically possible, and the annual electricity produced thereof, are shown in Table 4. For these calculations, the energy value of wet bagasse (50% moisture content on a wet basis) is taken as 7.7 MJ/kg. The following efficiencies are assumed: boiler, 70% at full load; steam turbine, 30% at full load; alternator, 96%; transmission, 98%. The overall plant efficiency at full load comes to 20%. Other data used for these calculations are indicated in the table.

The energy available is calculated from the amount of fuel (bagasse) available and the energy value of the bagasse. The power potential is determined from the energy input and the overall bagasse to electricity conversion efficiency, as assumed for this study.

It is seen that there is a potential to generate some 60 MW of electricity simply by changing to a more efficient conversion system.

Some 30 MW of power is already generated by the 4 mills. Thus an additional 30 MW of power can be generated. This would require using modern and efficient boilers, steam turbines operating on steam of a higher quality (in terms of pressure and temperature) and having modern alternators with efficiencies close to 94-96%. The annual electricity output, with 50% of the steam generated being used by the mills, comes to 200 GWh, which is around 40% of the current level of electricity consumption by FEA customers in Fiji.

Table 4 : Power Generation Potential Using More Efficient Conversion Processes

Mill	Cane Harvested (Mte/yr)	Sugar Produced (tonnes)	Bagasse Available Mte/yr; 50% mcwb	Energy Available GJ/yr	Power Potential MW	Annual Electricity GWh
Labasa	0.75	88018	0.09375	288750	11	80
Lautoka	1.75	205375	0.21875	673750	27	187
Penang	0.5	58679	0.0625	192500	8	53
Rarawai	1	117357	0.125	385000	15	107
Total	4	469428	0.5	1540000	61	428

Data Used:

Average TCTS	8.251
Energy value of dry bagasse	15.4 GJ/te
Moisture Content of bagasse	50% wet basis
Hours of full-load operation	7000 hrs/yr
Overall plant efficiency	20%
Fraction of dry bagasse in cane	0.125

(Source: Author's calculations)

Using Alternative Conversion Technologies

The current conversion process, as used by the sugar mills in Fiji and most of the sugar mills elsewhere, uses a boiler to generate steam and a steam turbine to convert the thermal energy of the steam into rotational kinetic energy, which is then used by an alternator to produce ac electricity. The Rankine cycle is thus used; its efficiency is limited to some 45%, with the best equipment that is currently available.

A number of technologies exist and are being used around the world to increase the conversion efficiency of bagasse to steam and to electricity. These are discussed below.

Gasification of the Bagasse

The raw bagasse, with a significantly high moisture content, is used as fuel input to a gasifier where the fuel is partially combusted and is then gasified. The major product emerging at the gasifier output is a mixture of gases, such as methane, carbon monoxide, hydrogen and carbon dioxide. The gaseous product needs to be thoroughly cleaned, cooled and either stored or piped to a gas turbine plant to burn the gas in a conventional gas cycle power plant to produce electricity.

Use of Gas Turbines

The use of gas turbines, with a combined cycle (Rankine) steam turbine will significantly increase the energy and the efficiency of the power generation. In the combined cycle mode, overall electricity to fuel input efficiencies of over 50% can be realized.

Using a gas turbine at high inlet temperatures, followed by a steam cycle, with the steam turbine operating at a pressure of, say, 2 MPa pressure and at 260^{C} temperature, the levels of power generation theoretically possible, and the annual electricity produced thereof, are shown in Table 5. For these calculations, the energy value of wet bagasse (50% moisture content on a wet basis) is taken as 7.7 MJ/kg ; and the following efficiencies are assumed: gasifier, 80% at full load; gas turbine, 35% at full load; steam turbine, 20% at full load; alternator, 96%; transmission, 98%. The overall plant efficiency at full load comes to 30%. Other data used for these calculations are indicated in the table.

Increase in Efficiency and Revenue

If the most efficient use of bagasse to co-generate steam and electricity is the target, then it will be necessary to run the power station on a continuous basis as well as on close to full load. This means that unless a suitable way is found to store bagasse and preserve bagasse to prevent its physical deterioration or deterioration in energy content, some other fuel or fuel combinations will have to be used.

The obvious fuel is wood, either in the form of logs, or sawmill waste products (hog fuel), which is readily available from the several sawmills that exist all over the country. Coal can be used as a backup for the woody biomass, although it will prove to be more expensive.

Table 5: Potential for Power Generation:
Use of Gas Turbine-Combined Cycle Power Plant

Mill	Cane Harvested (Mte/yr)	Sugar Produced (tonnes)	Bagasse Available Mte/yr; 50% mcwb	Energy Available GJ/yr	Power Potential MW	Annual Electricity GWh
Labasa	0.75	88018	0.09375	433125	17	120
Lautoka	1.75	205375	0.21875	1010625	40	281
Penang	0.5	58679	0.0625	288750	11	80
Rarawai	1	117357	0.125	577500	23	160
Total	4	469428	0.5	2310000	92	642
	Data Used:					
	Average TCTS			8.251		
	Energy value of dry bagasse			15.4 GJ/te		
	Moisture Content of bagasse			50% wet basis		
	Hours of full-load operation			7000 hrs/yr		
	Overall plant efficiency			30%		
	Fraction of dry bagasse in cane			0.125		

(Source: Author's calculations)

There are definite gains in efficiency to be made with respect to minimizing the moisture content in the fuel, whether it be bagasse, wood or coal. A study done several years ago (Prasad, 1988) on steam generation using a sawdust-fired monotube boiler system showed that the boiler efficiency can increase significantly as the moisture level in the fuel is decreased. The overall efficiency of energy conversion is also increased.

The energy cost of electricity, using the simple modeling employed for this study and using baseline data such as the installed cost of the higher pressure and temperature steam turbine generation system, the annual operational and maintenance cost, lifetime of the system, annual hours of operation of the power plant, interest rate, etc. shows that the energy cost varies from 11 c to 23 c/kWh, for a 60 MW steam power plant utilizing all of the bagasse produced, as well as secondary fuel such as woody biomass and/or coal.[5] For a 60 MW_e power plant, operating for 7000 hours per year, and generating electricity at 13 c/kWh, the revenue that can be generated, assuming the same charge as that levied by the FSC to its domestic consumers (i.e. 22c/kWh) by selling off the excess electricity (over that used by the sugar mills, assumed to be 50% of the electricity produced) can thus range from 11 to 27 million dollars annually depending on the moisture content of the bagasse and wood.

However, a detailed and full cost benefit analysis needs to be carried out on the economic aspects of power generation. This study was constrained greatly in that this sort of analysis was outside of the scope of this research. Such a study can establish that the FSC will gain substantially by generating electricity all year around and selling the excess at a competitive price to the FEA.

It would also be worthwhile to consider, in the present situation, converting the bagasse left over each year at the end of the sugarcane harvesting season to some sort of fertilizer. This should be relatively inexpensive to do on site and the fertilizer could then be sold to the farmers at an economic cost. This would ensure that all of the bagasse produced each year is usefully utilized.

Conclusion

A study, using available data from the FSC's sugar mills and theoretical aspects of power generation, has been made of energy aspects of the sugar industry in Fiji. Using data from the FSC, the production and consumption of bagasse, the major energy source driving the industry, has been incorporated into the largely theoretical study.

From this research, and within the constraints of the study, the following observations are summarized. First, bagasse is quite inefficiently used by the mills because of the low pressure and relatively

[5] Calculations are from the author's work in progress.

low temperature of the steam generated in the boilers. The overall power generation efficiency is around 5-7% only.

Second, bagasse can be more efficiently utilized if the boilers are modernized so that the steam pressure and temperatures are much higher. If this is done, then the heat and power needs can be met by using a significantly lower amount of the fuel than what is currently used. In this situation, the overall power generation efficiency would be between 15-20% and the efficiency of co-generating heat and electricity could be well over 50%.

Third, the use of bagasse gasification and the use of gas turbines and combined cycle technology, can greatly increase the energy output (both steam and electricity) and the energy efficiency of the sugar mills. The excess electricity can be sold to the national grid. The overall power generation efficiency, at full load operation, with this technology can reach 20% quite easily. The overall cogeneration efficiency can exceed 60%.

Fourth, for continuous and constant power generation, bagasse would have to be supplemented with some other fuel, such as hog wood from sawmills, or some other form of biomass or coal. Woody biomass, readily available from sawmills would present the best option.

Appendix 1: Notes on Energy and Power Units

The paper uses various energy and power units which are summarized in this Appendix.

Energy is the ability to do work, measured in the basic unit of the Joule (J).

Power is the rate of expenditure or production of energy, measured in the basic unit of the Watt (W). Thus 1W = 1 Joule/second.

For electricity, the more convenient unit of energy is the Watt-hour (Wh), defined as the power (in watts) used or produced by an electrical device or machine for a time of 1 hour. Thus a 100 Watt light bulb uses 100 W of power from the electrical mains and if it is used for an hour, it uses 100 x 1 hour = 100 Wh of energy per hour. In 10 hours it will consume 100 x 10 = 1000 Wh = 1 kWh of energy. Other units include the amount of energy contained in a tonne (1000 kg or a metric ton) of oil, called a tonne of oil equivalent (TOE). A MTOE is thus the energy equivalent to that contained in a million tonnes of oil. (1 MTOE = 1.7 TWh). The subscript `e' in $MW_e$ refers to `electrical'.

For larger amounts of energy and power, multiplier units (such as kilo, Mega, Giga and Tera) are used, as given below.

Measure of	Unit	Meaning	In Basic Units	Basic Unit Multiplied By
Power	kW	kilo Watt	1000 Watts	Thousand
	MW	Mega Watt	1000000 Watts	Million
	GW	Giga Watt	1000000000 Watts	Billion
	TW	Tera Watt	million x million Watts	Trillion
Energy	kWh	kilo Watt-hour	1000 Wh	Thousand
	MWh	Mega Watt-hour	1000000 Wh	Million
	GWh	Giga Watt-hour	1000000000 Wh	Billion
	TWh	Tera Watt-hour	1000000000000 Wh	Trillion

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