2. INTEGRATING SWEET SORGHUM INTO A SUGARCANE MILL

Because the integration of sweet sorghum with sugarcane is expected to use the existing sugarcane processing equipment found in sugar mills, and the growth of sweet sorghum has implications for both the agronomic and processing parts of the biofuel production chain it is necessary to describe the existing sugarcane systems and the points where sweet sorghum is likely to have a major impact in some detail. The systems and their impacts are described below.

Land Preparation
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Planting
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Crop Growth & Management
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Harvesting
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Unloading
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Juice Extraction (crushing)
9
Conversion

b 9 `

Electricity Sugar Ethanol

Text Box 1 **Process Flow Diagram of Sugar, Ethanol & Electricity Production**

2.1. Overview of an Existing Sugarcane-Based, Bioenergy-Producing System

The sugarcane mill at Triangle, Zimbabwe, is typical of sugar mills built in the 1940's and 50's. The process chain is summarised in Text Box 1. It has operated since opening with continuous maintenance and some improvements. Most noticeable, from the point of view of this work was the construction of an ethanol plant in 1981 for fuel ethanol production.

Sugarcane mills around the world range in cane processing capacity from 50 to 1050 $t_{cane}\ h^{-1}$ with an average capacity of about 400 $t_{cane}\ h^{-1}$ (Bauen, 1998). Therefore, with a processing capacity of 490 $t_{cane}\ h^{-1}$ Triangle Ltd.'s mill is slightly higher than the world average. In terms of energy consumption, Triangle's average energy consumption per t_{cane} of 570 $kg_{st}\ t_{cane}^{-1}$ is slightly higher than the average which is around 500 kg_{st} (Walter, 1994), and electricity consumption of 27 kWh t_{cane}^{-1} compares well with the average of 30 KWh t_{cane}^{-1} (Gopinath, 1997).

Where Triangle differs from the rest of the world is in its consistently high rates of sugarcane productivity of 115 $t_{cane}\ ha^{-1}\ yr^{-1}$ compared to 64 $t_{cane}\ ha^{-1}\ yr^{-1}$ which was the global average in 1998 as highlighted in Table 2.2.

2.1.1. The Production & Conversion Chain

A brief description of the complete production and conversion chain is provided below to give an overview of an existing production chain and to highlight areas where the integration of sweet sorghum will have significant impacts. (Text Box 1) These impacts are described further in the following sections.

2.1.1.1. Agronomy

Triangle's location in the semi-arid south east region of Zimbabwe was no accident. The estate and mill were deliberately located in this area because of good soils and the high levels of solar radiation throughout the year. The early construction of a large irrigation canal allowed water to be brought from a higher rainfall area so that the cane could be irrigated. Considerable investment has continued in the construction of dams and canals in order to ensure a reliable supply of water, even so in 1992, sugarcane growth ceased completely due to severe drought. The scale of the operation has meant that the estate is split into 300 to 400 ha sections, each of which is run on a semi-autonomous basis. This also means that some sections are a considerable distance from the mill and cane is brought to the mill from over 60 km away.

The sugarcane is grown on a 12 month cycle, and depending on the conditions for crop growth, harvesting occurs over a nine month season between mid-March and the end of December. However, because of sugarcane's ability to re-grow from the same roots after harvesting, called ratooning, new sugarcane stock is only replanted after 10 years growth. This has considerable implications for the integration of sweet sorghum as it affects both the availability of land after harvesting and the period the land is left fallow after the old cane root-stock is removed. A combination of short, medium, and long season varieties of sugarcane are used to maintain high levels of sugars in the stems over the entire harvesting period.

Land Preparation

The type of land preparation required at the beginning of each season depends on whether the old ratoon has been removed. Removal of the old ratoon requires deep ploughing and a minimum of a 3 month fallow period before the new sugarcane can be planted. Before planting, the topsoil has to be harrowed to break down the larger clods of soil and is then ridged. The ridging is essential for good drainage, and where furrow irrigation is applied (see below) the furrows channel the water evenly across the field. If the cane is to be allowed to regrow from the existing roots to form a new ratoon, the land is either thoroughly weeded, or a blanket of the old tops and leaves is left on the soil to prevent competition from weeds.

Planting

The old cane root-stock is removed after 10 ratoons (i.e after 10 years) because, if more ratoons are allowed then the productivity declines. Planting of new cane stock also allows the gradual replacement of old varieties of cane with newer, higher yielding clones or varieties. These may also be more resistant to the pests and diseases prevalent in the existing fields and have improved ‘quality’ characteristics such as higher sucrose purity and lower fibre content.

Planting of sugarcane is not carried out using seeds, instead billets (short sections of cane stems) are planted into the soil about 5cm down, producing new shoots from the internodes.

Crop Growth & Management

The efficient management of the crop from emergence through to harvesting is crucial to the overall economics of the entire system. Potential problems must be spotted early and dealt with before they threaten the crop. Irrigation is provided at regular intervals, dictated by the climate. Irrigation is carried out to keep the soil between 50% TAM and Field-Capacity[5], with the cane being irrigated to the equivalent of 2000 mm rainfall by maturity. Irrigation is withheld before flowering as this increases the levels of sugars in the stems and maturity agents may also be applied by aerial spraying. In addition to irrigation, the nutrient status of the soil must be kept at optimum levels (300 kg N ha^{-1} applied) and pesticides are applied to keep pests and diseases to a minimum.

Harvesting & Loading

Currently, virtually all sugarcane in southern Africa is manually harvested. However, trials are being carried out with mechanical harvesters which are routinely used in Australia and USA. Whilst labour costs are low, there is little incentive to purchase capital intensive mechanical harvesters, which can be expensive to purchase, maintain and repair. However, recently, it has been reported to the author that ‘as a result of AIDS both the numbers of labourers and their productivity has dropped. (Lonsdale, 1998; Wenman, 1999b) One unforeseen consequence of the AIDS epidemic may be a more rapid introduction of mechanical harvesting to Southern Africa.

The current practice for manual harvesters, who cut 5 or more tonnes of cane per day, is

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5 TAM (Total Available Moisture) is a measure of the amount of water available to the plant in the soil profile. Field Capacity is a measure of the total volume of water the soil is able to hold.

to stack the cane into 5 t bundles in the field. This cane is then collected by mobile cranes and placed directly into the waiting transporters at the side of the field. A second method, in operation in KwaZulu Natal, SA, is to cut the cane and leave it in rows in the field. A mechanical ‘grabber’ then follows the harvesting, collecting and putting it into a cart which is left in the field, or if the fields are serviced by rail, then the cane is put into waiting rail carts at the nearest point to the fields.

2.1.1.2. Transport

As with virtually all agricultural operations, the transport of the crop from the fields to the processing facility is often one of the key economic variables dictating profitability. This sensitivity of profits to transport results from the relatively low density of the final product (sugar) per unit volume of raw biomass i.e. a large volume of non-valuable material is transported with the main product i.e. water and fibre. Transport equipment is also relatively expensive in terms of capital and O&M costs.

With nearly 2.5 million tonnes of cane being transported to the mill each season, the mill receives about 25 separate deliveries per hour, and operates 24 hours a day. The co-ordination of the deliveries of cane is a considerable logistical operation, needing to match not only the rate of delivery with the mill capacity, but also requiring that the most mature cane arrives and is processed first.

As a result of the sensitivity of profitability to transport, there are a number of different transport types available. The type chosen depends on the:

< scale of operation,
< transport distance,
< costs per t.km
< to some extent on the age of the plantation & productivity i.e. the potential returns from long term investments.

At Triangle, there are three main types of cane transporters available:

<	'Hilo' (tractor and trailer- 20 t):	<20 km
<	truck (50 t, now seldom used):	>20 km
<	train (1000 t):	>20 km

2.1.1.3. Industrial Conversion

A description of the process by which the delivered biomass is processed to produce crystalline sugar, ethanol, and electricity is provided below. An aerial view of Triangle Sugar Mill can be seen in Figure 3. The production of waste and by-products is evaluated in the Discussion.

Fig. 3 Triangle Mill & Ethanol Plant, Zimbabwe (March 1998)

Unloading

As the cane arrives at the mill, it is weighed and samples taken to measure the fibre and sucrose content, with the value of each delivery being calculated from these parameters. After weighing, the cane is delivered to either the 66" mill tandem[6] or the diffuser lines. If it is delivered to the 66" mill line, the cane is craned off on to the loading conveyors. If it is delivered to the diffuser line by the Hilo's, which are specifically designed for use with the diffuser, then the complete Hilo is tipped up and the cane drops onto the diffuser-loading conveyors. The use of Hilo's with the diffuser is a very efficient and

[6] The '66" Mill' describes the width of the conveyor system (i.e. 66 inches wide) and therefore the process stream..

rapid unloading process. Loads can also be craned onto the diffuser line as shown in Figure 10.

Juice Separation (Crushing)

This is a critical stage in the processing chain from the point of view of bioenergy production, as after this stage there are at least three more potential processing routes for the sugars:

i	Crystalline sugar only:	the residual sugars, in the form of molasses, must to be disposed of through alternative non-fermentation routes e.g. cattle feed.
ii	Sugar & Ethanol:	molasses to be 'disposed' of by fermentation to produce ethanol and CO_2.
iii	Ethanol only:	after crushing the juice is routed directly to the fermentation plant and no crystalline sugar is produced.

There are two methods for the separation of the sugars from the fibre. The older technology employs a mill tandem which effectively squeezes the sugar-rich juice from the fibre. The second method, called 'diffusion', extracts the sugars by washing them out of the fibres. The diffuser employs a counter-current flow of hot water flowing against the fibres to achieve this. Two primary streams exit these processes, i.e. i) the sugar rich juice, and ii) the fibre-rich bagasse.

Under the current configuration at Triangle, the juice goes through a three stage sucrose removal process resulting in the removal of 92% of the sucrose in the juice. The remaining sucrose, other sugars, and residual dissolved solids i.e. 'C' molasses, are then sent to the fermentation plant. The fermentation residue called 'stillage', is disposed of by mixing with irrigation water and then by irrigation on the cane fields.

Bagasse Use

In sugarcane stems, the fibrous (structural) matter i.e. bagasse, and the sugars are present in approximately equal amounts (by fresh weight mass) in the stems i.e. 12 to

15% each. As a result of going through the juice separation process, virtually all the sugars are removed from the fibres. The addition of water during the crushing process means bagasse exits the crushing process at about 50% moisture and it has an energy density of 7.6 GJ/t compared to 17 GJ/t if oven dry.

The plant is designed to ensure that during the milling season the rate of bagasse consumption for energy production is roughly equal to its production, which minimises bagasse disposal problems. Therefore, virtually all the bagasse is burnt in boilers to raise steam, some of which is passed through back-pressure turbo-altenators to produce electricity. Some steam is also passed through auxiliary turbines to provide rotary power for the mills and pumps, and the remainder is used for heat requiring processes as shown in Figure 4. Surplus bagasse can be stored and used out of the crushing season which is discussed in more detail in Section 5 (the Discussion).

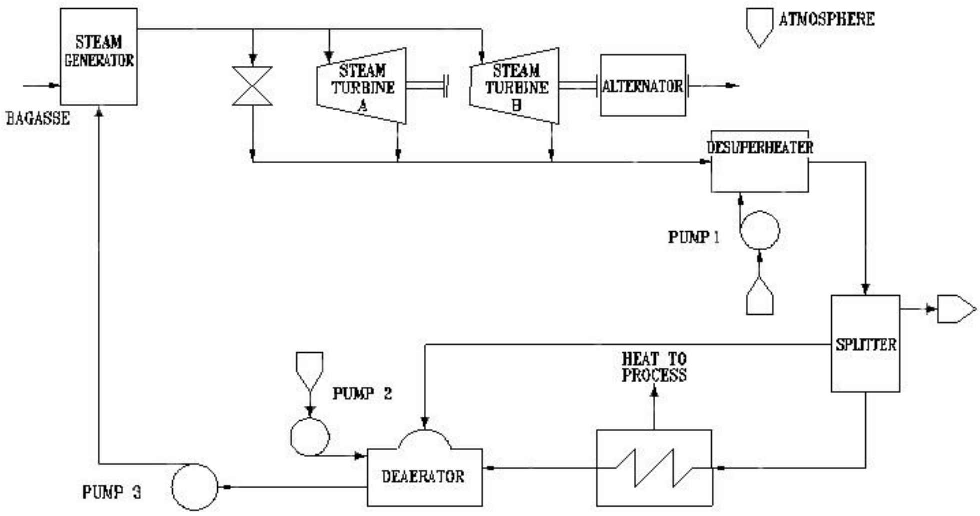

Fig. 4 Standard Back Pressure Steam Turbine Mill Set-up for Direct Power and Electricity Production (Walter, 1994)

During normal operation, the bagasse supplies the total energy requirements for the crushing, sugar, and ethanol production processes, and 7 MW_e to power the irrigation pumps; on average, a total electricity supply of 19 MW_e is required. In addition to the electricity, motive and heat energy are supplied to the mill by steam generation from bagasse. The total energy demand supplied by bagasse to the mill, and for irrigation, is 270 MW providing 220 MW_{th} of high pressure steam. The potential electricity production from the bagasse would be sufficient to supply about 15 000 households in the UK with electricity i.e. a medium sized town.[7]

It is worth noting that three of the ten bagasse-fired boilers can burn coal in addition to bagasse, with the coal being burnt to supply power during the off-crop, when the mill is being repaired, and during the scheduled maintenance periods. Some bagasse is also supplied to the animal feed plant where it is used as a bulking agent.

Use of the Juice

Once extracted from the cane stems the juice can be processed to produce crystalline sugar or ethanol, or a combination of both. See below for a description of the processes.

Crystalline sugar production. The sucrose is extracted from the juice through a three stage evaporation process resulting in the production of crystalline sugar and 'C' molasses. 300 000 t of crystalline sugar are produced from the 2.5 million t_{cane} processed each season at Triangle Ltd. i.e. 1 t sugar for every 8 t_{cane}. The process of extracting the sucrose is energy intensive, requiring the evaporation of the bulk of the water from the 644.6 t h^{-1} of clear juice produced by the diffuser and 66" mill lines. Power is also necessary for the centrifuges which separate the crystals from the molasses. Depending on the relative value of the sucrose as crystalline sugar, or ethanol, the molasses can be sent to the fermentation plant after each of the 'B', or 'C' molasses stages.

Ethanol production. Since 1981, Triangle Ltd., has been running a 40 Ml per year capacity ethanol fermentation plant for the production of fuel alcohol. The plant initially supplied the internal gasoline market with anhydrous ethanol-blended fuel and was constructed to address problems of 'national energy security'; economic considerations were of secondary importance. More recently, the combination of high

7 Assuming an electricity production efficiency of 35% of energy input and a per household consumption of 5 kW_e. i.e. 270x0.35 = 95 MW_e

value sugar quotas in export markets and relatively cheap supplies of petroleum have enhanced the value of crystalline sugar relative to fuel-ethanol. Therefore, Triangle Ltd. has reconfigured its plant to maximise crystalline sugar production from sugarcane at the expense of ethanol production, producing only 23 Ml in 1998. A surplus capacity of 17 Ml now exists.

However, there is also an international market for ethanol mainly driven by environmental requirements of ethanol as a fuel oxygenate in the United States and Europe, and as a petroleum substitute in Brazil. In addition, there is a strong potable ethanol market with the European Union providing protected (high value) markets via quotas to some developing countries (Berg, 1998a). Despite the recent fall in the prices of crystalline sugar to an all-time low on the world markets and an associated reduction in ethanol prices, if sugar or ethanol can be sold into European or US quotas then profits remain high.

2.2. A Novel System to Produce Bioenergy from an Integrated Sorghum / Sugarcane System

This section describes the main issues involved with developing an integrated sweet sorghum / sugarcane bioenergy production system, and is again based around the Triangle Ltd. Sugar mill located in Zimbabwe. The assessment of the impact of sweet sorghum growth is based on the considerable body of research derived from small-scale trials on sorghum agronomy carried out world wide over the last two decades (see Table 1.1). It is also based on sweet sorghum trials carried out in the Triangle area (some on Triangle Ltd.'s land) monitored by the author and described in Table 2.1 (Mvududu *et al.*, 1998; Woods *et al.*, 1996)

An overview of existing and future potential productivities is given below for both sugarcane and sweet sorghum, followed by a review of the potential impacts of integrating the two crops. No discussion of the impacts on transportation is provided, as it is assumed that the same equipment, currently in use for sugarcane, will be used for sorghum and sugarcane.

Table 2.1: Agronomic Trials Monitored by the Author during this Research

Location	Funder*	Date	Notes
Triangle (Zimbabwe)	CFC	13th Dec 98 to 31st March 1999	Productivity, partitioning, sugars, on existing sugarcane fields (Keller only)
Chiredzi (Zimbabwe) (Mvududu *et al.*, 1998)	CFC	30th Nov 98 to 31st Mar 1999	Full partitioning, soil, pests and diseases, multi-variety (predominantly Keller & Cowley)
Chiredzi (Zimbabwe) (Woods *et al.*, 1997)	CFC	21st Nov 97 to 15th Mar 98	CFC Sweet Sorghum trials
Chiredzi (Zimbabwe) (Woods *et al.*, 1996)	EU	20th Feb 97 to Jun 97.	Productivity and Partitioning analysis
Chiredzi (Zimbabwe) (Woods *et al.*, 1995)	EU	7th Jan 95 to May 95	Productivity and Partitioning analysis
Chiredzi (Zimbabwe)	EU	18th Dec 93 to 1st Apr 94	Productivity and Partitioning analysis
Triangle (Zimbabwe)	EU	Sep 93 to Feb 94	Productivity and Partitioning analysis
Chiredzi (Zimbabwe)	EU	30th Aug 93 to Dec 93	Productivity and Partitioning analysis
Bucharest (Romania) (Roman, 1995)	EU	1995 15th May to Sep 95	Sweet & Fibre varieties: Productivity and Partitioning analysis
Monterotondo (Italy) (Massacci *et al.*, 1996)	EU / CNR	1993, 1994, 1995	1993 (Grain Sorghum) then Sweet Sorghum

Notes: * Funding bodies: CFC - Common Fund for Commodities; EU - European Union; CNR - National Research Council, Italy.

2.2.1. The Agronomic Impact of Sorghum Integration

The potential agronomic impacts that could result from the integration of sweet sorghum with sugarcane are described below. From a crop management perspective, the competition between sorghum and sugarcane for resources needs to be quantified and ameliorated. From the industrial perspective, the timing of the availability, and the biomass quality are crucial parameters. A potential impact which would be extremely difficult to quantify, but is important none the less, is the change in perception by the sugar industry about the relative benefits of bioenergy versus crystalline sugar production and the potential for sweet sorghum. The implications of this kind of change in perception are discussed in detail by Alexander (1985). He states that increases in total sugar production will be easier to achieve if plant breeding and cane production is re-oriented towards maximising biomass production and not simply by concentrating on sucrose production. His analysis is also highly relevant to sweet sorghum, where only recently have efforts been made to select high-yielding biomass varieties.

However, potential problems resulting from a crop rotation system which uses a C_4 crop following another C_4 crop, such as the build up of pests and diseases will only be seen in a full scale trial, and continuous production over a number of years (see Pests & Diseases below). However, research has been carried out directly inter-cropping maize with sugarcane, and suggests that such problems can be overcome with good management (Wallace *et al.*, 1991). Such management would ensure that in an inter-cropping system the competition for nutrients and water between the two crops is minimised mainly by ensuring that applications are sufficient in quantity and timing (Wallace *et al.*, 1991). It is anticipated that these problems will be manageable in the integrated sweet sorghum / sugarcane system as a result of the perennial nature of sugarcane and the relatively short periods of time the sorghum will be grown in these fields. Furthermore, the direct intercropping of sweet sorghum with sugarcane is not proposed here, instead a 'co-cropping' system where sweet sorghum and sugarcane share adjacent, and not the same, fields.

2.2.1.1. Crop Production

An overview of existing, and future, potential productivities is given below for both sugarcane and sweet sorghum, followed by a review of the potential impacts of integrating the two crops.

Annual Productivity

It is important to realise that sweet sorghum is not in competition with sugarcane in terms of yields or biomass quality. The primary aim is to use land and equipment which cannot be used for sugarcane during specific periods of the year. However, to ensure economic viability, the integration of sweet sorghum into the agronomic schedules of a sugar estate must result in an overall increase in the yields in terms of total biomass and sugars on a yearly rather than seasonal basis. Importantly, the integration should not result in an increase in inputs per unit output i.e. fertilisers, pesticides, herbicides, energy inputs, etc. should not increase per t of biomass exported from the fields to the mill.

Sweet Sorghum Yields

Yields of over100 t_{fab} ha^{-1} have been achieved around the Mediterranean with 5 months growth (Roman, 1995). The yields achieved in Zimbabwe have been lower primarily due to lower temperatures and radiation levels and the results from the Zimbabwean trials are presented in section 4.2. With careful selection of varieties, good management and optimal planting times it should be possible to obtain 80 t_{fab} ha^{-1} in 4 months (8000 g m^{-2} equivalent to 1344 GJ ha^{-1} LHV[8]). The proportion of this above ground biomass allocated to tops and leaves is 20%, leaving just over 60 fwt_{cane} ha^{-1} stems for harvesting. With careful selection of varieties for high biomass and high sugar, about 13 % total fresh stem mass will consist of fermentable sugars. Yields of this magnitude will only occur on a larger scale through practical experience and a lower yield of 60 t_{fab} ha^{-1} i.e. 46 t_{stems} ha^{-1} is used for the rest of this research. This topic is discussed in more detail in the Discussion chapter.

Sugarcane Yields

FAO (1999) data for sugarcane yields in 1998, gives a worldwide average annual productivity of 64 fresh weight tonnes cane stems per hectare (fwt_{cane} ha^{-1} yr^{-1}), which is equivalent to 20.4 oven dry tonnes (odt_{cane}) ha^{-1} yr^{-1} as shown in Table 2.2. However,

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8 Average sweet sorghum whole plant energy content of 16.9 GJ odt^{-1} HHV (Table 4.4)

FAO yields only account for stripped cane stems as delivered to the mill. They do not therefore take into account the residual tops and leaves (green & dead) which are traditionally removed from the cane stem at harvest (and sometimes burnt in the field to reduce transport costs and to recycle nutrients). These tops and leaves represent a considerable extra reserve of biomass, a portion of which can be collected and used for energy production.

Table 2.2: World Sugarcane Yields and Energy Content

Region / COUNTRY	FAO[1] 1998 Yields t_{cane} ha^{-1} yr^{-1}	Total Biomass[2] odt_{tb} ha^{-1} yr^{-1} (FAO*0.609)	Energy[3] Prodn GJ ha^{-1} yr^{-1}
World	63.6	38.7	678
Industrialised Countries	87.2	53.1	929
Developing Countries	62.6	38.1	667
Zimbabwe	113.1	68.9	1205
Zambia	110.0	67.0	1172
Egypt	110.8	67.5	1181
Peru	115.3	70.2	1229

Notes:

1. 1998 yields: FAO AGROSTAT Database (FAO, 1999): FAO quotes yields of millable sugarcane stems as delivered to the sugar mill. These yields therefore do not account for residual biomass such as the tops & leaves left on the fields. See note 2 below.
2. Total above ground biomass, in odt, includes: millable stems (54%) +(tops + attached leaves + detached leaves(46%)). The average composition of sugarcane, total above ground biomass (tb), at harvest is as follows (Legendre, 1995): 70% moisture (wet weight basis), 13-15% sucrose, 13-15% fibre.
3. Energy Content of Sugarcane plus residues = 17.5 GJ odt_{tb}^{-1} (Hall, 1993)

When tops and leaves are added to cane stems, total above ground biomass comes to 38.7 odt_{tb} ha^{-1} yr^{-1} assuming that there is 0.609 odt_{tb} for each fwt_{cane} harvested (64*.609) (Hall *et al.*, 1993). For example, Zambia's cane productivity in 1998 was 110 fwt_{cane} ha^{-1} yr^{-1} or 67 odt_{tb} (110*0.609), using the factors given above, to include tops and leaves. Average yields in 1998 are shown in Table 2.2. However, there is considerable variation between countries. The high variation in national yields and data from the literature strongly suggests that present yields are at the low end of possible yields and is discussed further in section 5.1.1.

2.2.1.2. Land Availability

Assessing how much land is potentially available for a novel use can be complex and emotive, both in developing and industrialised countries. It is inextricably tied in with local and national issues of land tenure, food production, and resource utilisation which makes a dispassionate and logical analysis often difficult. The use of dedicated land areas as an energy supply resource can only be justified if that resource allows a net gain in food supply either: i) directly by allowing irrigation from ground water using pumps driven by the bioenergy or ii) by the production of cash crops which can be used to purchase that food. Economists quantify these "problems" by assigning an economic value to all the inputs and outputs required for a specific crop. Therefore, if one crop is to be displaced (or efficiently compete) with another crop its net economic returns must be greater than the crop it replaced.

Where under- or non-utilised land is available then there is no competition. However, as in most cases, the new crop will have to compete with existing forms of land use. In Zimbabwe, sweet sorghum's most likely competitor as a cash crop on fallow land is cotton and therefore the net returns from sorghum will have to exceed those from cotton. In order to successfully compete for land resources, it must first be shown that the sorghum is technically capable of producing sufficient yields of the primary product under the conditions it will be grown.

The technical evaluation of available land area can be carried out using mathematical models which compare the value of the final product against mean transport distances for a defined centralised processing plant and "catchment" area, as described by Nguyen and Prince (1996) and evaluated in section 4.5.2.1.

These models are sensitive to:

- productivity
- cost + efficiency of transport per unit mass and distance i.e. $ per t.km
- factory process costs and efficiencies

Their utility lies in the ability of these models to define tightly the parameters which will allow economic production of a commodity. Therefore, when used in conjunction with an analysis of the physical availability of land, a supply curve of the most cost effective land areas can be produced indicating which areas should be used first.

Cropping Patterns

As a result of the 10 year ratooning pattern discussed earlier, it might be expected in any one year that 10% of the land under sugarcane would be left fallow and be available for sorghum growth. However, for reasons primarily due to the timing of availability of this land, only about half of this fallow land can be considered for sorghum growth.

A clear advantage of the proposed co-cropping system is that there is a synergy between the timing of the availability of this fallow land and the optimum period for sweet sorghum growth. The end of the sugarcane harvesting season in November / December coincides with the start of the rainy season in Zimbabwe when rainfall, solar radiation and temperatures are at their highest. These conditions are optimal for the growth of sweet sorghum. This is also true for the sugarcane crop which assimilates a significant proportion of its final carbon stock during these critical growth months. Therefore, if inter-cropping of sweet sorghum with sugarcane were practised, it could lead to significant competition between the two crops and a reduction in net crystalline sugar production per year. Thus, the sweet sorghum will be grown using fallow land in a co-cropping system, and inter-cropping will not be considered.

2.2.1.3. Crop Management

A number of factors influencing the integration of sweet sorghum and sugarcane can be overcome or mitigated by good crop management regimes. The main areas are outlined below.

Water Use and Availability

Irrigation is currently applied to sugarcane using a combination of syphon (gravity) and over-head sprinkler systems. The water is generally supplied from a network of dams and canals, and in Zimbabwe, considerable investment has gone into the construction of new dams over the last decade.

In many parts of the world, water availability is a major concern as storage and supply resources are becoming more fully exploited and are therefore gaining a greater monetary value. The fact that the water resource is becoming constrained has been reflected in the price of irrigation water experienced by farmers in the Lowveld region of Zimbabwe. Ten years ago irrigation water was virtually free. However, over the last four years its cost has risen from Z$ 13 to Z$ 30 m^{-3} in 1997 and is expected to cost over Z$ 60 m^{-3} in 1999. Therefore, systems are required which make the most efficient use of water resources and provide the best return per unit of water.

Nutrients

Fertilisers are currently applied by hand in granular form and may be re-applied after heavy rainfall. The recycling of stillage through irrigation returns a significant proportion of the phosphates and potassium to the fields and reduces synthetic fertiliser application. Similar profiles of nutrient extraction can be expected between sweet sorghum and sugarcane when the crops are of similar age i.e. during sugarcane's first year of growth, as they are both physically similar and both produce sucrose as the dominant sugar type. However, after sugarcane's first ratoon, different soil extraction profiles can be expected, resulting from different root length densities by soil layer between an annual and ratooning crop.

The AIP, by using the INRA-CERES sorghum model, can be used to assess the nitrogen requirements of the crop by soil type and the potential for N leaching if the soil components are properly calibrated.

Pests & Diseases

A number of pests and diseases are common to both sweet sorghum and sugarcane and their incidence and control will need to be carefully monitored. Under Zimbabwean conditions where sugarcane is grown on a 12 month growth cycle superimposed on a 10 year ratooning cycle, a significant fallow period only exists when an old ratoon is being removed and the field undergoes replanting with new germplasm. The recent increase in the incidence of ratoon stunting disease (*Clavibacter xyli* subsp. xyli [9]) has meant a strict enforcement of the 4 month fallow period between removal of the old ratoon and replanting. This period represents an ideal opportunity for the growth of sweet sorghum. However, if sweet sorghum is shown to be able to propagate this disease, then control measures will be required in infected fields.

Other diseases which affect both crop types are:

- Stem borer
- Maize black beetle

Harvesting

There are two main areas where sweet sorghum may behave differently from sugarcane. The first area is based on physiological differences between sorghum and sugarcane in that peak sugar levels in sweet sorghum are reached whilst the leaves are still green. As a result, removal of the leaves by burning prior to harvesting may prove difficult and if harvested with the stems a decrease in sugar levels in the delivered biomass may also result.

The second area where problems may be foreseen results from the need to harvest the sweet sorghum before the sugarcane. This will inevitably result in harvesting occurring during the rainy season (November to March) with wetter soils making access to the fields more difficult for heavy mechanical equipment. Strategies will need to be developed to cope with both these differences which are analysed in more detail in the Results section. 4.2.1.

Soil Carbon

It is not expected that the integration of sweet sorghum with sugarcane will have any significant effect on in-field soil carbon balances in the longer term i.e. over more than one ratoon cycle. However, the growth of sweet sorghum on fallow sugarcane land that would otherwise have been left undisturbed, could result in losses of carbon from the

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[9] This is a bacterial pathogen which survives in the host, and can't be transmitted by seeds. It therefore, tends to survive in the residual sugarcane roots after harvesting.

soil as a result of increased soil disturbance. The dynamics of soil carbon balances under agricultural conditions is extremely complex and will need monitoring to establish whether or not the growth of sweet sorghum on fallow land will result in net emission or sequestering of carbon in the soil.

Legal / Social

Under current Zimbabwean laws, only sugarcane is covered by legislation which makes it illegal to carry out unauthorised harvesting. Sweet sorghum is grown locally by communal farmers (and in garden plots) for grain, fodder, and as a delicacy when eaten in its raw state. Personal communications with sugarcane estate managers have shown that they believe estate-grown sweet sorghum may prove vulnerable to theft. Therefore, without a change in legislation, some losses may be expected towards maturity but prior to harvesting.

2.2.2. The Industrial / Conversion Impact of Sorghum Integration

The supply to the mill of significant amounts of sweet sorghum (i.e. requiring more than 2 weeks of mill time) during the ‘off-crop’ will have implications for the management of the mill. During the off-crop, the mill is completely shut down, and undergoes extensive maintenance in order to minimise problems during the subsequent crushing season. With this period of maintenance becoming somewhat restricted, strategies will need to be put in place to ensure that the efficient operation of the mill is not compromised. Furthermore, as sweet sorghum has never been processed on a commercial scale in a sugar mill (to the author’s knowledge), crushing and use of the juice will need to monitored carefully to ensure that unforeseen problems do not arise as a result of the differences in composition between sorghum and sugarcane.

Whilst problems resulting from the processing of ‘clean’ sweet sorghum stems are expected to be minimal, processing of stems + leaves could prove more difficult. However, during the initial phases of sweet sorghum processing it is proposed that exactly the same processing methods used for sugarcane are used for sweet sorghum. Therefore, no changes in the configuration of equipment or in equipment types will be necessary if the tops and leaves are stripped from sweet sorghum stems just before (or during harvesting), and only the stems are delivered.

A brief discussion of the anticipated impacts of processing sorghum using the existing mill setup is given below:

Juice Separation (Crushing)

Differences in the fibre composition as compared to sugarcane may cause problems if juice separation is carried out by diffusion. Problems were experienced at Triangle's mill in 1998, when novel cane varieties which were 'low-fibre' were crushed. These varieties had higher 'pithiness' than previous varieties and this change in fibre particle size caused filter plate blockages, making it impossible to run the diffuser with these varieties alone. Mixing of the low and higher-fibre varieties has now solved this problem, and may be necessary with sweet sorghum which from visual estimates seems more pithy than sugarcane (Wenman, 1999a). Recent tests at Triangle Ltd. during the 1998 and 1999 seasons have shown that sweet sorghum is capable of being processed by either the 66" mill or the diffuser technologies. (Section 4.3.3)

Bagasse Use (Steam and Electricity Generation)

No problems are expected with the combustion of the sweet sorghum bagasse using the existing boilers. The combustion technology used is extremely robust and not prone to failure. Whilst there is considerable potential to increase the efficiency of the steam and electricity generation process, the existing technologies are not expected to be problematic in using the sweet sorghum bagasse for power production.

Sugar and Ethanol Production

Fermentation tests and sugar analysis carried out on sweet sorghum stems by the Zimbabwe Sugar Organisation show that sweet sorghum juice (from cv.s Keller & Cowley) is well suited to ethanol production (Mvududu *et al.*, 1998). Therefore, if sweet sorghum juice is sent directly to the fermentation plant no problems are foreseen in the production of ethanol.

However, literature surveys from research in China and India have stated that crystalline sugar production may be more problematic (Liu *et al.*, 1997; Nimbkar, 1997). These reports stated that the higher levels of starch and aconitic acid[10] found in sweet sorghum juice, inhibited the crystallisation process. As no crystallisation tests have yet been carried out to the author's knowledge on Keller or Cowley-derived juice, more research is needed here. Methods do exist to remove aconitic acid from process streams, but the sensitivity of profits to this extraction, if necessary, has not been analysed here (Malmary *et al.*, 1995).

2.3. Novel Technologies for Converting Biomass to Bioenergy

In a bioenergy producing sugar-mill, there are three primary outputs i.e.:

1. Crystalline sugar
2. Ethanol
3. Electricity

To an extent, there is a competition for resources between these outputs. For example, there is a direct play-off between sugar and ethanol production in the allocation of sucrose to these outputs. To a lesser extent, there is competition for the energy content of the bagasse between electricity production and the power and heat requirements for sugar and ethanol production. New technologies can help in this respect by increasing the efficiency with which these products are produced in terms of their energy intensity.

Relevant technologies for improved efficiency of bioenergy production exist for virtually every stage of the process chain, from land preparation through to waste disposal. The range of commercialised technologies for the sugarcane industry is large, and no attempt is made here to categorise or analyse the relative benefits of technologies on a consistent basis across the entire production chain. The AIP has been designed to allow an assessment of the impact of novel, or new-to-that-location, technologies at

10 Aconitic acid is a secondary plant product, believed to be involved in protecting the plant against insect (aphid) action (Rustamani *et al.*, 1992).

each stage of the process chain, but there is no consistent data within the AIP to do this at present unless the data are inputted. Instead, the AIP is designed to provide a structure to allow these technologies to be assessed against a ‘default’ mill setup.

The information provided in this section is therefore limited to an evaluation of novel technologies relevant to bioenergy production from the integrated sugarcane / sweet sorghum process chain, and not to technologies which could bring incremental increases in efficiency to sugarcane-based crystalline sugar production.

Furthermore, whilst the introduction of sweet sorghum itself can be regarded as a novel technology, the agronomic issues involving its introduction have been discussed above. To the extent that the introduction of mechanical harvesters is novel to both the sugarcane and sorghum schedules, mechanical versus human harvesting will be discussed, but the standard existing agronomic technologies won’t be discussed in great detail unless relevant to energy production (see section 4.3.1).

2.3.1. Liquid Fuels

The demand for biologically derived ethanol for use as a biofuel is expected to increase as Industrialised countries in particular try to cut carbon emissions associated with the transport sector. The energy balances associated with non-sugarcane based bioethanol programmes have lower energy output to input ratios. Eventually this may drive these countries to a significant commitment to develop new technologies. At the moment, fermentation technology dominates the production of ethanol and is already an efficient process. Therefore, only fermentation technologies are highlighted below. It is worth pointing out that the production of ethanol is already a large-scale business, and in 1998, world ethanol production was estimated at 32 billion litres up from 29.9 billion litres in 1995 (Berg, 1998b).

2.3.1.1. Fermentation

The most commonly used feedstock for ethanol production in developing countries is sugarcane, which is used primarily as a result of its high productivity when supplied with sufficient water. Advantages of sugarcane feedstock include the high residue energy potential and modern management practices which make sustainable and environmentally acceptable production possible whilst at the same time allowing continued production of sugar (Scurlock *et al.*, 1991). Other feedstocks include saccharide-rich sugarbeet, and carbohydrate-rich potatoes, cassava, wheat, maize, and of-course sorghum.

Industrial Ethanol Production

Ethanol production results predominantly from aerobic fermentation which is a simple batch-type biological process. However, it is prone to problems concerning contamination, over or under-heating, and the effect of fermentation inhibitors in the substrate. At face value, the dominant contaminating organisms will be fermenter-type organisms, with unplanned fermentation occurring virtually from the moment the stem is cut until active steps are taken to sterilise the substrate. Losses due to contamination of the harvested stems by fermenting bacteria significantly constrain the period available between harvest and processing and therefore require the close coupling of the rate of harvesting to the capacity of the conversion plant (sugar mill, ethanol plant), dictating a post-harvest storage time of hours rather than days or weeks.

Semi-continuous and continuous fermentation systems do exist with the main aim of these systems being to keep the yeast alive and to reduce sugar losses associated with the new growth of yeast. The use of flocculent yeasts, centrifugal yeast removal and partial by-pass distillation are examples of upgraded fermentation systems.

<u>Anaerobic fermentation for stillage pre-treatment:</u> Anaerobic reactors are generally used for the production of methane-rich biogas from manure (human and animal) and crop residues. They utilise mixed methanogenic bacterial cultures which are characterised by defined optimal temperature ranges for growth. These mixed cultures allow digesters to be operated over a wide temperature range ie. above 0ºC up to 60ºC. When functioning well, the bacteria convert about 90% of the feedstock energy into biogas (containing about 55% methane). The sludge produced is non-toxic and odourless and has lost relatively little of its nitrogen or other nutrients during the digestion process thus making it a good fertiliser. In digested sludge little of the

nitrogen is volatised, and some of the nitrogen is converted into urea which is readily accessible by plants.

Modern designs have answered many of the earlier problems with reliability and ease of use, so that now digesters are useful for removing toxic nutrients such as nitrates from water supplies; levels of which are now much more stringently controlled in many industrialised countries. The combination of energy production with the ability to enhance crop yields make biogas technology a good candidate for more widespread use now that reliable operation can be demonstrated.

Were anaerobic digestion to be implemented in the sugarcane mills, its main function would be to treat waste-water streams, such as stillage, to lower the BOD and COD. The methane production would then be an ancillary energy benefit and the effluent could be added directly to the irrigation water.

2.3.2. Electricity and Process Heat & Power Production

Once it is established that there is a market for the increase in electricity produced by the mill, then an evaluation of the technologies available for the production of the electricity (and steam for process power) is required. In virtually all cases, the mill will want to produce 'base-load' i.e. continuous supplies of electricity, as this is more valuable in comparison to the intermittent supplies often produced by other forms of renewable energy technologies i.e. wind, PV, and to some extent hydro. However, base-load power production will require either the storage of bagasse for use out of the harvesting season, or the use of an alternative fuel for this period i.e. gas or coal.

In an integrated sweet sorghum / sugarcane system the period when the mill is not producing bagasse will be shorter. Providing the period when sweet sorghum is processed is sufficiently long, it could be possible to generate a bagasse surplus to enable year-round power generation. Currently at Triangle Ltd., a small amount of bagasse is kept in storage, but the remainder of the surplus is incinerated as the storage capacity is limited.

Recent developments in combustion technology, including circulating fluidised bed systems, have led to increases in the efficiency with which biomass residues can be used for steam generation. However, for electricity generation, the generation of steam as an intermediary step to electricity generation using condensing extraction steam turbines (CEST) results in an inherent loss in energy in the boiler heat exchangers when compared to direct combustion systems such as closely coupled gasifier/gas turbine systems (see below). CEST turbines are more efficient than back pressure turbines (Figures 4 & 6) in terms of electricity production, but as a result the exhaust steam has too low temperature and pressure for use in providing process steam. Hence CEST turbines are generally used when there is excess high pressure steam or no requirement for process heat. Electricity generation technologies using natural gas and fuel oils with gas turbines overcome this energy loss, as the fuel is burnt directly in the combustion chamber of the turbine, obviating the need to generate steam. The development of gasification technologies has now reached the point where biomass (and coal) can be gasified and therefore used with gas turbines, and it is this technology which promises to revolutionise the way biomass is used in the future for electricity generation.

Gasification / Gas Turbines

Research is now being carried out with the aim of increasing energy production (electricity and heat) from sugarcane mills through the integration of novel biomass conversion technologies (gasification coupled to aero-derivative gas turbines) and high efficiency steam utilisation technologies. It is estimated that within 5 years, sugar mills could increase their electricity production at least 10 fold worldwide simply by using cane residues more efficiently, for example see: Waldheim, 1998; Gabra, 1995; Williams, 1993. The potential impact of the installation of gasification systems at Triangle Ltd. Mill is evaluated in section 4.4.1.5. and Table 4.27.

Gasification has existed since the turn of the century when coal was extensively gasified in the UK and elsewhere for use in houses for cooking and lighting. Gasifiers were also widely used to power transport vehicles in Europe during World War II due to shortages of oil, with a closed top design predominating. A major future role for gasification technologies is envisaged in electricity production from biomass plantations and agricultural residues. These systems will use large scale gasifiers (5 to 30 MW_e) with direct coupling to gas turbines. The potential gains in efficiency using such hybrid gasifier/gas turbine systems make them extremely attractive for electricity generation once commercial viability has been demonstrated. A number of demonstration plants of scales relevant to the sugar industry are now being constructed, and are discussed in the Results section.

Such systems take advantage of low grade and cheap feedstocks (residues and wood produced using short rotation techniques) and the high efficiencies of modern gas turbines to produce electricity at comparable or less cost than fossil-fuel derived electricity. The use of BIG/STIG (Biomass Integrated Gasifier Steam Injected Gas Turbine) initially and BIG/GTCC (Biomass Integrated Gasifier Gas Turbine Combined Cycle) as the technology matures, is predicted to allow energy conversion efficiencies of 40% to 55% (Figures 5 & 6). Large scale (500 to 1000 MW_e) modern coal electrical plants have efficiencies of about 35% or less. Combined Heat and Power systems could eventually provide energy at overall efficiencies of between 50% to 80%. The use of low-grade feedstocks combined with high conversion efficiencies makes these systems economically competitive with cheap coal-based plants and energetically competitive with natural gas-based plants (Makunda *et al.*, 1992; Williams and Larson, 1993). However, before BIG/GT systems can compete successfully with the conventional combustion / boiler systems currently in operation, they will need to demonstrate:

< comparable installed costs
< comparable or better reliability
< improved efficiency in electricity and steam generation

With these BIG/GT demonstration projects now underway (Section 4.4.1.5) estimated costs for electricity generation are now becoming more reliable.

The fibrous residues (bagasse, tops, and leaves) can either be burnt directly to raise steam, which in turn can be used to generate electricity or provide direct heat and power

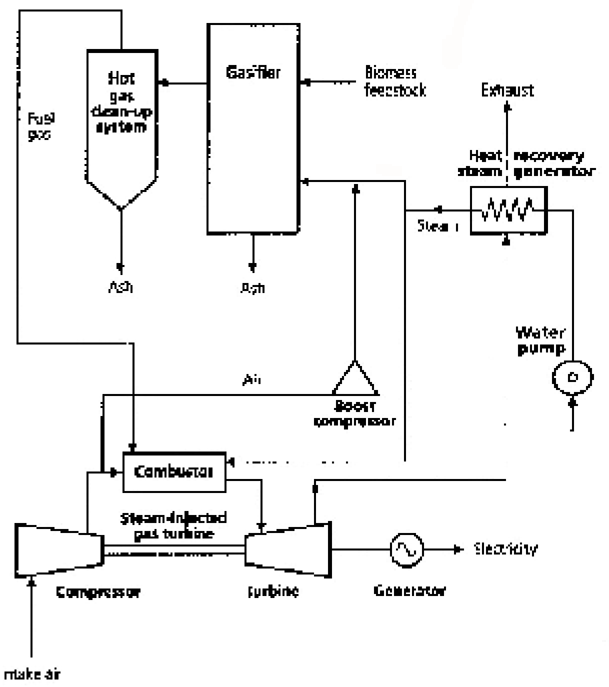

Fig. 5 Biomass Integrated Steam Injected Gas Turbine (Williams and Larson, 1993)

(Figure 4), or gasified to produce producer-gas (Figure 5). The producer-gas thus derived, can be used to generate electricity (very efficiently) by coupling the gasification systems to gas turbines, with the exhaust gases being passed through a heat exchanger to raise high pressure steam. Further electricity can then be generated by using this steam in a bottoming cycle and/or using it as process steam for direct power applications as shown in figure 6. Overall, gasification systems for electricity generation will result in an increase in electricity production at the expense of process steam production.

Fuel Cells

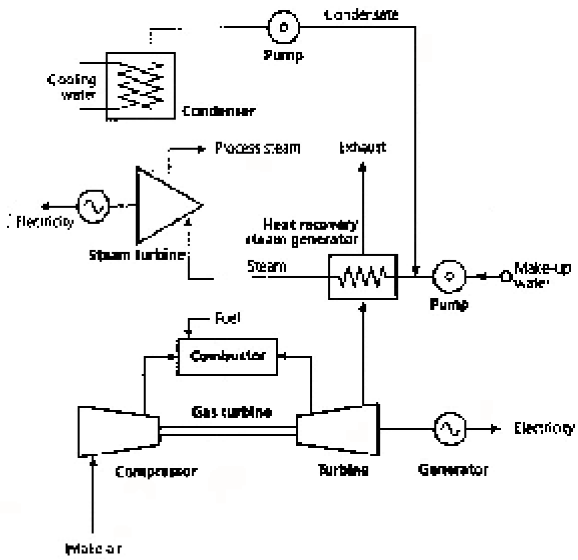

Fig. 6 Gas Turbine with Steam Combined Cycle (GT/CC) with Process Steam recovery (Williams and Larson, 1993)

The combustion of the syngas produced by the gasifiers in the gas turbines means that the maximum conversion efficiency is set by the 'Carnot' limit at approximately 60% of the energy content of the fuel being converted to electrical energy. Fuel cells, which use electro-chemical principles to convert hydrogen to water have the potential to by-pass the 'Carnot' limit[11] (Williams and Larson, 1993). For example, an advanced aeroderivative gas turbine with a combustion temperature of 1573 EK (1300 EC) and an exhaust temperature of 673 EK (400 EC) has a theoretical limit to the efficiency of 57%. Fuel cell technology is at the pilot scale demonstration phase, but is still a relatively expensive technology compared to the BIG/GT systems discussed above i.e. expected costs are 400 $/kW installed (Bauen, 1999; Williams and Larson, 1993). Also, the overall efficiency of the two systems needs to be compared. In the BIG/GT systems the 'waste' heat from the turbine exhaust is not lost to the atmosphere, instead it would be used to generate process steam for use in the mill. If fuel cells were installed in sugar

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[11] The Carnot-limit is simply: $1-(/T_{exhaust}/T_{input})$
where T_{input} = input temperature to turbine & $T_{exhaust}$ = turbine outlet temp.

mills, many of the processes which are currently supplied with energy by steam would need to be converted to electricity, and an overall evaluation of the conversion efficiency would be required to see if this would represent an improvement compared to BIG/GT. Fuel cells are not discussed further in this thesis.