Integrating Sweet Sorghum and Sugarcane for Bioenergy: Modelling The Potential for Electricity and Ethanol Production in SE Zimbabwe

A thesis submitted for the degree of Doctor of Philosophy

by

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ABSTRACT

This thesis describes a new agriculturally-based bioenergy system which integrates sweet sorghum (*Sorghum bicolor* L. Moench), a rapid growth (3-5 months), C_4 sweet-stemmed annual crop, with the perennial crop sugarcane (*Saccharum officinarum*, 12-18 months growth period), to improve:

the length of the harvesting season
the efficiency of production of ethanol & electricity
the efficiency of use of land, water, equipment, personnel, & other resources

The research involved the development of a novel, prototype, systems-analysis model called the 'Agrosystems Integration Package' (AIP), which has been developed to:

assess the impact of integrating sweet sorghum with sugarcane at a specific site
optimise the selection of technologies to produce bioenergy (ethanol, electricity, and heat) from the sweet sorghum / sugarcane system

That such a novel bioenergy system can be integrated with existing sugarcane-based bioethanol systems is evaluated by using the Triangle Ltd. Sugarmill and sugarcane estates, located in the semi-arid region of southern Zimbabwe, as a model system. The potential for co-cropping sweet sorghum with sugarcane was assessed both agronomically and in the agro-industrial conversion phase. It was concluded that sweet sorghum could be grown for harvesting during the sugarcane 'off-crop' when the sugarmill and equipment is normally idle. In addition, there is a good potential for year round processing and therefore biofuel production in an integrated sweet sorghum and sugarcane system. The viability of the integrated system is dependent on maintaining high sugarcane yields and achieving sustainable and high sweet sorghum yields. During this work sweet sorghum yields of over 70 tonnes above ground fresh biomass per hectare have been achieved for a single crop cycle at Triangle.

Because sorghum is adapted to semi-arid areas and makes optimum use of scarce resources such as water and nutrients, its use should result in net improvements in the resource use efficiency for bioenergy production on sugar estates. In summary, this research has evaluated:

i. the site specific potential for bioenergy production from sweet sorghum
ii. physical resource requirements, i.e. water, nutrients and land
iii. manpower needs, itemised by skill level
iv. a basic economic evaluation
v. energy, carbon, and nitrogen balances

Dedication to Prof. David Hall

David died on the 22nd August 1999 whilst I was in the final stages of writing up my thesis. Throughout the 10 years that I worked with him on the research into the potential to use sweet sorghum for energy, and a multitude of other bioenergy related issues, he continued to be the inspiration to me that he was when we first met. I was aware of, and sometimes assisted with, many of the wider research issues that David took a world-leading role in such as: climate change, environmental law, land-use policy, and biohydrogen production (with Krishna Rao in is his research labs). However, after his death, it became clear that David was a well known figure-head in many other developmental areas that I knew little or nothing about. Looking back now, David tried to show that an integrated approach to all these issues is critical not just to the survival of the human race but to making this world a fit place for all its inhabitants, human and non-human, to live.

In fact, David was one of those rare and inspirational figures who had a coherent overview of the framework within which the world's people and crucially its environments could have a positive future together. Some of the people who have that kind of vision find the day-to-day experience of dealing with other people tiring or indeed tiresome, but not David. He revelled in human contact and the mental development that comes through discussions and exchanges with other researchers and students to whom he was always available. He was ceaselessly interested in the views and company of others, which is reflected in the huge network of previous students of his who now hold influential positions in both the research and policy sectors around the world.

Of course it is now up to those of use who worked closely with him to carry the torch of his work. To me, this is most clearly defined as the relationship between the provision of clean and renewable energy and development for all, especially the rural people of the developing countries. Perhaps, by continuing with this work I can repay his memory in some small way for all that he did for me.

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Gerry (my mother) and Paul Mitchell (not my mother) helped with the final hurdle by enabling me to believe that the thesis was finally ready to submit through the ultimate sacrifice of actually reading it. Steve Collins provided invaluable help during the initial stages by firstly, helping me believe that the topic is worthy of a PhD and secondly, with the initial structure, both of which are so crucial to getting started.

The research undertaken during this PhD has been funded through three European Union projects (JOULE 2, PECO, & APAS) and carried out in collaboration with the Biomass User's Network Zimbabwe, the European Sweet Sorghum Network (ESSN), the Bioclimatologie Institute of INRA (France), CNR (Italy), and Triangle Ltd. Zimbabwe. In all of these institutions there are people to whom I owe a debt of gratitude, but none more so than to the late Prof. David Hall my tutor, mentor and inspiration in so many things both within and outside the bioenergy world.

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Glossary- Abbreviations & Units.

Conversion Units. (all in Lower Heating Values, LHV). Except where stated "t" refers to an oven dry tonne (odt) of biomass (1,000 kg, approximately 0% moisture)

Energy Contents (unless otherwise stated).

1 t Bagasse = 7.6 GJ (50% m/c)
1 t Coal = 30 GJ
1 t Charcoal = 28 GJ
1 bbl = 1 barrel oil = 159 litre = 1/7 t
1 l Diesel = 39 MJ (c.f. fuel oil)
1 l EtOH= 21.2 MJ (LHV, 23.4 HHV anhydrous, 99.6 GL)
1 l Fuel Oil = 36 MJ (39 HHV, 0.86 kgC)
1 l Gasoline = 30.1 MJ LHV (34.9 HHV, 0.76 kgC)
1 t Oil Equiv. (TOE) = 42 GJ (MTOE = 1 million TOE)
1 t HP steam = 2.88 GJ (380 C, 3.1 MPa)
1 t wood = 15 GJ (air dry, 20% mc; 20 GJ, 0% mc)

Acronyms.

AN = Ammonium Nitrate
AWS = Automatic Weather Station
BIG = Biomass Integrated Gasifier
BP = Back Pressure (turbine)
BOD = Biological Oxygen Demand
CFC = Common Fund for Commodities
COD = Chemical Oxygen Demand
DSSAT = Decision Support System for Agrotechnology Transfer
e (as subscript) = electricity
EtOH = ethanol
EU = European Community
ISTIG = Intercooled STIG
CHP = Combined Heat and Power
CEST = Condensing Extraction Steam Turbine
CRS = Chiredzi Research Station
FW = fresh weight
GEF = Global Environment Facility of the World Bank
GHG = GreenHouse Gases
GT = Gas Turbine
GTCC = Gas Turbine Combined Cycle
GUI = Graphical User Interface (on computers)
HP = High Pressure (steam)
hp = horse power
HHV = Higher Heating Value
IEA = International Energy Authority
LHV = Lower Heating Value
LUE = see ‘RUE’
mc = moisture content (wet weight basis)
MSW = Municipal Solid Waste
MW_e = MW electricity
MW_{th} = MW thermal (or heat)
NPP = Net Primary Productivity (t ha^{-1} yr^{-1})
NUE = Nutrient Use Efficient
odt = oven dry tonne
Offcrop = out of sugarcane harvesting season
O&M = Operation & Maintenance
PAR = Photosynthetically Active Radiation
PET = Potential Evapo-Transpiration
P/PET = Precipitation/PET
PV = Photovoltaics
R_g = Global Radiation (Solar)
RME = Rape Seed Methyl Ester
RUE = Radiation Use Efficiency (g/MJ_{PAR})
SOM = Soil Organic Matter
SRWC = Short Rotation Woody Coppice.
STIG = Steam Injected Gas turbine
t = tonne (1000 kg)
t_{steam} = tonne steam
TA = Turbo Altenator
WEC = World Energy Council
WUE = Water Use Efficiency
ZSA = Zimbabwe Sugar Association (Research Station)

International Units.
J = Joule = 0.24 calories
h = hour
1 ha = hectare = 2.47 acres = 10000 m^2
t = metric tonne = 1,000 kg.
1 btu (British Thermal Unit) = 1.054 kJ
1 calorie = 4.19 J
1 kWh = 3.6 MJ
1 MWh = 3.6 GJ
1 W = 1 Js^{-1}
n = nano = 10^{-9}
µ = micro = 10^{-6}
m = milli = 10^{-3}
k = kilo = 10^3
M = mega = 10^6
G = giga = 10^9
T = tera = 10^{12}
P = peta = 10^{15}
E = exa = 10^{18}

Chemical.
CO_2 = carbon dioxide
CH_4 = methane
CH_3OH = methanol
C_2H_5OH = ethanol
H_2O = water
C = carbon
N = nitrogen
P = phosphorous
Phosphate = P_2O_5
Potash = K_2O
K = potassium

Sugar Measurement Acronyms
BRIX = Total Dissolved Solids in Juice
ERC = Estimated Recoverable Crystal (Sucrose)
ERF = Estimated Recoverable Fermentables
Fibre = Undissolved Stem Mass (primarily cellulose and lignin)
PI = Preparation Index
Pol = 'Polarity'; measurement of sucrose content.
RS = Reducing Sugars
Sucrose Purity = (POL/BRIX)x100
TFAS = Total Fermentables as Sucrose
TFS = as above
UFRS = Unfermentable Reducing Sugars

Biomass Units
(for energy contents see 'Energy Contents' section above)
odt = oven dry tonne
t_{fab} = tonnes total above ground fresh weight biomass
t_{cane} or t_c = tonnes sugarcane stems (fresh weight as delivered to the mill)
t_{stems} = tonnes sweet sorghum stems (fresh weight as delivered to the mill)

Sweet Sorghum Maturity Points
Booting = production of reproductive organs, visible by swelling at top of stem
Flower / Anthesis = the emergence of the flowers
Grain Filling = start of deposition of starch in the grains
Milking = Milky substance visible if grains squeezed, equivalent to Soft Doe
Hard Doe = Grains do not crush easily when squeezed and no milky substance is extruded. Equivalent to the end of grainfilling.
Photoperiod = day length
Photoperiodism = response of crop growth to day length

1. INTRODUCTION

This thesis describes a new agriculturally-based bioenergy system which integrates sweet sorghum (*Sorghum bicolor* L. Moench) with sugarcane to improve:

the length of the harvesting season
the efficiency of production of ethanol & electricity
the efficiency of use of land, water, equipment, personnel, & other resources

The research involved the development of a novel, prototype, systems-analysis model called the 'Agrosystems Integration Package' (AIP), which has been developed to:

assess the impact of integrating sweet sorghum with sugarcane at a specific site
optimise the selection of technologies to produce bioenergy (ethanol, electricity, and heat) from the sweet sorghum / sugarcane system

The work arose from the concerns of the late 1980's and early 1990's, covering a broad range of bioenergy related issues, such as rural development, energy security, and climate change. This convergence of global environmental concerns has combined with the emergence of new, highly efficient biomass energy conversion technologies, and a political imperative to protect rural economies. As a result, a profound change in the perception of biomass energy has now occurred. 'Bioenergy' has begun to be perceived not as a historical energy source of last resort, but as a sustainable energy resource for the future. This re-assessment of bioenergy derives from four main factors: 1) biomass is available virtually everywhere (i.e. anywhere plants grow); 2) it has inherent, 'free', energy storage characteristics, unlike the other renewable energies; 3) it can be converted into solid, liquid, and gaseous energy carriers; and 4) there are large quantities of agricultural residues produced globally which are generally under-used.

However, there are problems associated with the use of biomass. For example, in its natural state, the biomass is often dispersed, has considerably lower energy densities than comparable fossil fuels, and may have competing end uses. Furthermore, it is now better understood that badly managed use of biomass resources can have negative impacts on the environment e.g. de-vegetation, soil erosion, loss of biodiversity, etc. (Hall and Scrase, 1998; AFREPREN, 1997).

Even with these reservations, it is now widely accepted that biomass will provide modern energy services (light, heating, cooling, etc..) well into the next century (Hall, 1999; IIASA, 1998; Shell, 1996; IPCC, 1995). Furthermore, its wide spread use could result in a number of secondary benefits being derived. (IPCC, 1995; Woods and Hall, 1994; Hall *et al.*, 1993; Johansson *et al.*, 1993)

These benefits include:

- sustainable, rural development with job creation
- a strong complementarity to other intermittent renewable energies
- improved health for rural populations who have access to clean fuels for lighting and cooking.
- increased food production when integrated with bioenergy

Bioenergy research and development efforts are concentrating on using newer technologies to increase the efficiency with which existing and future biomass resources are used. For example, at the household level in developing countries, improved cooking stoves increase the combustion efficiency and ease of use, decreasing both the emissions from cooking and the amount of biomass required. Crop residues and firewood are usually the feedstock for these types of energy use. (Smith, 1992) However, the provision of more convenient types of energy carrier (i.e. liquid or gaseous fuels, and electricity) can require the development of dedicated biomass crops which can produce high quality products such as sugars, fibre, oils, and starch. For example, unless expensive pre-treatment technologies are used, crops or residues without the naturally high levels of sugars found in sugar-rich crops (e.g. sugarcane, sugarbeet, or sweet sorghum) cannot be used to produce ethanol. Therefore, dedicated energy crops often need to be grown to supply specific conversion technologies, and are now being developed to meet these specifications and provide modern fuels eg. sweet sorghum for ethanol, short rotation coppice for electricity and heat, oil seed rape for biodiesel.

The future use of these ‘energy crops’ will depend on the demand for energy and the ability of these crops to supply energy competitively within the national and international policy environment of the next century. The future demand for bioenergy is assessed in the next section.

1.1. Future Requirements for Bioenergy

‘Climate Change’ is gradually being accepted as a measurable phenomenon by the global community (IPCC, 1996). Implicit in this acceptance is the need to switch away from fossil fuels to more sustainable, non-polluting sources of energy. Unlike the 1970's and 80's, the switch to renewable energy is not being driven by the belief that fossil fuel resources are about to be exhausted (Campbell, 1997). A number of strategies designed to respond to the need to reduce the emissions of greenhouse gases (GHGs) predict that bioenergy (a CO_2-neutral fuel) will supply a significant proportion of the global energy supply in the next century. Even in Shell’s ‘Sustained Growth’ scenario (otherwise known as ‘business as usual’) biomass is predicted to supply 14% of the world’s primary energy supply which itself virtually quadruples from present supply (390 EJ) to 1500 EJ in 2060. In their ‘Dematerialisation’ (conservation driven) scenario, total energy use in 2060 is less than 940 EJ, with fossil fuels and nuclear power providing 41% of the total. Biomass provides 207 EJ (22% of the total), with 157 EJ from dedicated bioenergy sources. Solar and wind provide 36 and 144 EJ, respectively (Figure 1; IEA, 1998; NAS, 1996; Shell, 1996). Whilst there are other forces encouraging the use of bioenergy, including energy security, rural development, increasing population in developing countries, and the scale of the resource; climate change is currently the dominant issue at the global scale encouraging the use of bioenergy.

In order for bioenergy to achieve its predicted share of the energy market, it will need to supply energy to all the main energy sectors i.e. industry, transport, domestic, and agriculture. Therefore, as described above, bioenergy will have to arrive at the consumer in convenient-to-use solid, liquid, and gaseous forms. Thus, unless biomass can provide cheap electricity and liquid fuels, it will never achieve the levels of penetration into the modern power sectors predicted by Shell, WEC, and others. As energy crops, sweet sorghum and sugarcane can be converted to produce liquid fuel (ethanol), heat, and electricity. However, the bioenergy derived will need to compete effectively with alternative energy sources and be produced in a sustainable, environmentally acceptable manner.

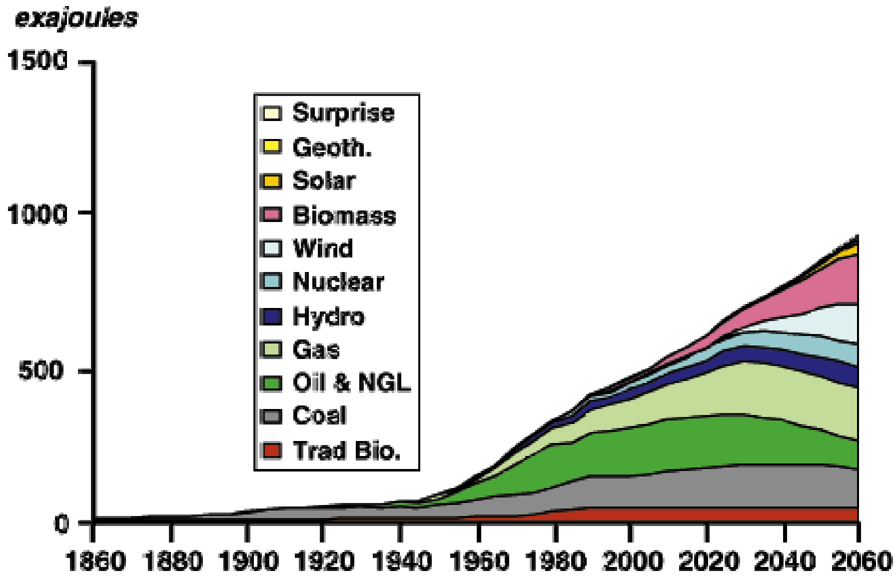

Fig. 1 Predicted Breakdown of Global Total Primary Energy Supply by Source 1860 to 2060- 'Dematerialisation Scenario' (Shell, 1996)

The liquid fuel sector is dominated by the consumption of petrol (gasoline) and diesel (including gasoil, fueloil, etc). Therefore, biomass-derived ethanol must be able to integrate with the petrol and / or the diesel sub-sectors unless an entirely new ethanol-only market is developed eg. Brazil (Goldemberg *et al.*, 1993). In fact, ethanol can be used as a liquid fuel in one of four ways:

1. Neat Ethanol
2. Blended with Petrol

3. Blended with Diesel
4. Octane enhancer

If biofuels are to supply significant amounts of electricity, then bioenergy technologies must be able to generate baseload electricity.[1] Biofuels must exploit their inherent advantage compared to other renewables, in that solar energy is stored in the structural components of plants, and unlike wind or PV, biomass energy can be stored at the conversion plant and therefore used for continuous generation. Until cheap, reliable, and large-scale electricity storage technologies are developed, solar and wind energy can only be exploited when the sun shines or it is sufficiently windy, hence their characterisation as 'intermittent renewables.'

Sweet sorghum can be grown for both ethanol and electricity production, and a considerable research effort has gone into the development of sweet sorghum for biofuel production in the USA, Europe and southern Africa over the last 30 years. However, because sweet sorghum is an annual crop, bioenergy production from sweet sorghum alone is inherently seasonal, making it unsuitable for year-round biofuel production if grown by itself. Fortunately, there is the potential to integrate the production of sweet sorghum with sugarcane to increase both the efficiency and duration with which bioenergy could be produced. Care is needed in implementing such an integrated system because the logistics of doing so are complicated and the range of applicable technologies is wide.

In this thesis, it is hypothesised that sweet sorghum can be integrated with sugarcane to allow the year-round production of biofuels, i.e. ethanol and electricity, in a profitable and environmentally sustainable agro-industrial system. In order to address the issue of complexity a systems analysis tool has been developed called the 'Agrosystems Integration Package' (AIP), which is described in Section 1.3. and 4.6.1. Chapter 2 provides an overview of an existing sugarcane-based bioenergy producing system, highlighting areas where the efficiency of production could potentially be increased. A

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[1] 'Baseload' is the term used for the continuous supply of electricity, and is not affected by fluctuations in demand which are met by 'peaking capacity' which can be turned on and off rapidly.

description of a theoretical, integrated sweet sorghum / sugarcane system is then described.

1.2. Why Sweet Sorghum?

Sweet sorghum is one of an increasing number of biomass crops which can be used to produce bioenergy at scales which are practical for rural communities and industries. The sugars obtained from the sweet stems can be extracted and fermented to produce ethanol for use as a liquid fuel, primarily for transport purposes. Ethanol is also used on a small scale in ethanol-fuelled lights and cookers. Electricity is currently a by-product of sugarcane-based crystalline sugar production and is derived from the combustion of sugarcane bagasse. However, in future, it may become one of the primary products as more efficient generating technologies are introduced. The fibrous residues obtained from the extraction of sugars from sweet sorghum stems can be used in the same way as sugarcane bagasse to produce electricity, process heat and power.

Generally, when sorghum is considered, it is the ‘grain’ rather than the ‘sweet’ varieties of sorghum which are highlighted. The relatively higher profile of grain sorghum results from its widespread use wherever poorer farmers cultivate water-scarce land. As its name suggests, grain sorghum is grown almost exclusively for its grain, which like maize or wheat can be ground to produce ‘flour’ for bread making, and fermented for beer making. In the poorer regions of many developing countries, grain sorghum provides the staple foodstuff for survival (NAS, 1996).

Sorghum has now been bred into 4 distinct groups:

grain (flour, beer)
fibre (fibre board, paper, cardboard, etc)
multi-purpose (grain, sugars, fibre, fodder)
sweet (primarily sugars)

Each of the sorghum groups benefits from the basic hardiness and productivity that characterises sorghum, and each has areas of relative advantage depending on its application. Of the four types, the 'multi-purpose' varieties aim to provide high levels of all the potential sorghum 'products' i.e. grain, fibre, and sugars. This has led to these varieties being called the 'four-Fs' varieties after their ability to produce "fuel, fodder, fibre, and food" (Li, D., 1997; Doggett, 1988). In this work, only the sweet varieties of sorghum are considered which maximise the potential for ethanol production.

In developmental terms, it is fair to say that sorghum has played a significant role in the poorer areas of developing countries. It is in these regions where, primarily the grain varieties of sorghum have been used by farmers to allow the production of food when inputs for other 'green revolution' type crops have been too expensive or un-available. Its robustness is the main reason that sorghum has been the crop of choice for farmers in drought prone regions, as it can survive low water and nitrogen (fertiliser) inputs and is relatively tolerant to salinity and drought stress. This survival role characterises the use of grain sorghum. However, the other sorghum types, i.e. the fibre, multi-purpose, and sweet- types, are being used to play an active role in engendering development as opposed to the crisis management role of grain sorghum. Generally, the primary aim with the non-grain types of sorghum is to optimise the productivity of high quality products to sell as cash crops, with the income being used for rural development.

Through intensive agronomic research over the last decade in the USA, Australia, Brazil and Europe, sweet sorghum has emerged as a viable feedstock for fuel ethanol production (Table 1.1). Its potential is based on the combination of advantageous agronomic characteristics described above. In addition, it has one of the highest intercepted radiation use efficiencies (RUE's) of any plant species, on a par with sugarcane, so allowing it to grow rapidly under optimal conditions. Moreover, its real potential lies in its growth under sub-optimal conditions where the combination of high RUE with high water and nutrient-use efficiencies, allow it to continue producing a sugar and fibre rich stem when other crops would struggle. (Gosse, 1995b; Woods *et al.*, 1995; Muchow and Coates, 1986)

Table 1.1: A History of Modern Sorghum Research (1970 to present)

Duration	Region	Co-ordinator	Project Title
1997 to present	Zimbabwe	J. Gopo	CFC/ISO Project: "Demonstrating Increased Resource Use Efficiency by integrating sweet sorghum with sugarcane"
1995-1996	Developing Countries	D.O.Hall & J. Woods, (KCL)	EU Project "The Production of Electricity & Biofuels Through the integration of Sweet Sorghum into the Sugar Industry in Developing Countries."
1992-1995	European Union	G.Gosse (INRA)	AIR Concerted Action: "Sorghum, A Crop for Industry and Energy Supply"
1992-1995	European Union & Developing Countries	D.O.Hall & J. Woods (KCL)	JOULE II Project "Bioethanol Production from Sweet Sorghum: interchange of research and experience between EC and developing countries (Zimbabwe and Thailand)."
1985-1992	France	G.Gosse (INRA)	INRA "Sweet Sorghum Productivity & Modelling"
1980's to present	China	Li Dajue, Lu Nan, (CAS, SAU)	A national research programme has been continuing for the last decade.
1980s (still continuing)	USA, Australia	Vanderlip (KSU) Ferraris, Muchow & Coates. (CSIRO)	Kansas State University "Development of SORKAM model." University of Hawaii (and others) "Development of Sorghum CERES model" Australian Studies in Queensland to integrate with Sugarcane Industry
1970's	USA	Arkin (TA&M)	Texas A&M "Development of SORGF model"
1980's to present	India	N.Nimbkar & A. Rajvanshi (NARI)	As part of National Indian Research Prog for Sorghum, continuous research is being carried out into the use of multi-product sorghum for energy, sugar, fodder, starch, etc.

Under good conditions, sweet sorghum varieties can outperform sugarcane in terms of total biomass production over short periods. However, problems persist with relatively low levels of 'sucrose purity'[2] which may initially rule out sweet sorghum as a candidate for large-scale commercial crystalline sugar production. Sweet sorghum's rapid growth and ability to reach maturity in 3 to 5 months, when coupled to its lack of

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[2] *Sucrose purity* is a measure of the percentage of the total dissolved solids in the extracted juice which is sucrose i.e. (POL/BRIX.)x100 (see Glossary for definitions of POL & BRIX)

photoperiodism (see below), are favourable to its production on fallow sugarcane land primarily because it can be grown and harvested before the start of the sugarcane harvesting season. High yielding varieties have now been developed which are capable of producing well over 100 t_{fab} (fresh weight tonnes of above ground biomass) in 5 months under good agronomic conditions compared to 150 t_{fab} over 12 months for sugarcane. Of course, this level of yield can only be achieved where climate, water and nutrient inputs are optimal and pests and diseases are fully controlled. However, the production of sweet sorghum benefits from the fact that it takes less water to produce per t above ground biomass than sugarcane, significantly reducing the amount of water required per litre of ethanol produced (Roman, 1995; Woods *et al.*, 1995). This is an important factor in the drought prone sugar-producing regions of the world.

Much of the world's crystalline sugar is derived from sugarcane produced on a 12 month (or longer) growth cycle (El Bassam, 1998; ISO, 1998). Unfortunately, as sugarcane is a photoperiod-sensitive crop, sugar accumulation is dictated by day length and is therefore seasonal. This seasonality defines the period during which it is economically feasible to harvest the cane and extract the sucrose and therefore, the mill plant cannot be used out of season, i.e. during the 'off-crop'. Despite this 'idle' time normally being taken up by refurbishing the equipment in preparation for the next season, there is scope to increase the length of the milling season significantly by changing mill management techniques.

By contrast, sweet sorghum is generally not photosensitive and when given sufficiently high temperatures for growth, it can reach maturity out of the sugarcane harvesting season. Therefore, the off-crop period when a sugar mill is not being used to process sugarcane provides an ideal opportunity for sweet sorghum to be processed if an economically viable output can be produced. It is this potential to use sweet sorghum to extend the milling season in existing sugarcane processing facilities which has provided the possibility of generating economically viable supplies of bioenergy from sweet sorghum and which this work seeks to exploit. The potential for exploitation is critically sensitive to the logistics of the integration which needs to be carried out in such a way so as to exploit the synergies between sugarcane and sweet sorghum and minimise potential problems.

1.3. Integrating Sweet Sorghum with Sugarcane

A number of paper-based studies have attempted to calculate the potential impact of an integrated sweet sorghum / sugarcane energy production system, e.g. Ferraris (1988), but to-date no significant attempts have been made assess the detailed and practical impacts of such an integration (Ferraris, 1988; Energy Authority of NSW, 1986). No other studies have used the combination of computer-based crop and systems modelling in conjunction with industrial scale process tests in existing sugarcane processing facilities to assess the potential for using sweet sorghum for bioenergy production.

It was proposed that sweet sorghum could be planted on fallow sugarcane land on the Triangle estates, Zimbabwe, for harvesting and processing during the off-crop season i.e. before the sugarcane is mature. The length of the period during which sweet sorghum is available for processing at Triangle Ltd., Zimbabwe, will depend on:

- the planting date
- the land area available from September to March; both on and off the sugarcane estates.
- season length of variety planted i.e. short (3 months), medium (4 month), or long-season (5 month)
- crop management: including any feedback loops between sorghum and sugarcane
- the minimum biomass quality parameters acceptable to the mill
- the processing rate of the mill
- the market for products
- the impact of new technologies if introduced
- government policies towards energy and environmental issues

The fact that sugarcane mills stand ‘idle’ for significant periods of time as a result of the inability to produce mature sugarcane out of season, provides the ideal opportunity for sweet sorghum to be processed during this period. Furthermore, the in-built lack of energy efficiency found in most of the world’s sugarcane mills and the unavoidable delivery of a large energy source to the mill (i.e. the bagasse) provides a second significant opportunity for increasing bioenergy production. However, sugarcane mills are large and complex operations, but where well managed, they are demonstrably sustainable[3]. Therefore, care should be taken when proposing radical changes to their operation, as changes in one part of the production chain can have unforeseen consequences in other parts.

The technical challenge is: (a) to reduce ethanol and electricity production costs whilst increasing the volume of production, (b) without affecting crystalline sugar production, and (c) with a methodology which is applicable to other sugar producing regions. If this is achieved, significant increases in electricity and process energy production are possible and an extension to the mill's energy production season can result. This is an important economic consideration for sugarmills, and the wider region.

Before such a novel ethanol, heat, and electricity producing system could be regarded as acceptable, it will have to demonstrate:

Positive energy balance
Sustainability
Economic viability
Applicability
Complementary integration with existing processes
Demonstration of integrated gasification- gas turbine technology (see below)

Since sweet sorghum has not yet been grown so that it can be integrated with sugarcane growth schedules, a theoretical assessment on the integration is carried out in Section 2. This 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 over the last two decades in Europe, Southern African and China and the use of the AIP (Table 2.1.).

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3 The author has visited a sugarcane field in Barbados where sugarcane has been grown continuously for over 300 years.

1.4. The AIP (Agrosystems Integration Package)

The scale and complexity of the sugarcane-based, sugar production system tends to make the owners and managers of sugar estates and mills conservative in their take-up of new technologies and management practices. Systems analysis tools which allow the impacts of new technologies to be assessed over the whole system can reduce the risks associated with implementing these new technologies. The AIP has been developed here to help assess these risks and with the aim of enabling the industry to become willing to consider adopting new, more sustainable technologies or management practices more readily. An overview is provided in Figure 2. In the case of bioenergy production from the proposed integrated sorghum / sugarcane system, changes in technology and management will need to be evaluated at a number of points in the process chain. Using the AIP, the risk of implementing new technologies before the need to invest in them arises can be assessed with greater ease and accuracy.

Furthermore, whilst a biomass energy project may be successful in one location, problems can be encountered when replicating such a project in another location. Historically, policy makers and entrepreneurs have sometimes failed to recognise the complexities involved with bioenergy schemes which are often critically dependent on site specific factors. Thus the introduction of new bioenergy technologies may have unforseen knock-on effects and needs careful site-specific planning. In order to achieve site-specificity, it has been necessary to couple mechanistic crop growth models (sweet sorghum and in the near future sugarcane) to the AIP, thus providing predicted sorghum (and sugarcane) biomass yields for a specific location and climate. The coupling of the sorghum and sugarcane models to the AIP allows analysis to be carried out on the impacts of novel technologies at more than one location, if sufficient data is available. With this information the AIP will allow economic and technical decisions to be made on the site specific viability of sorghum systems, including the potential impact of advanced conversion technologies and crop varieties.

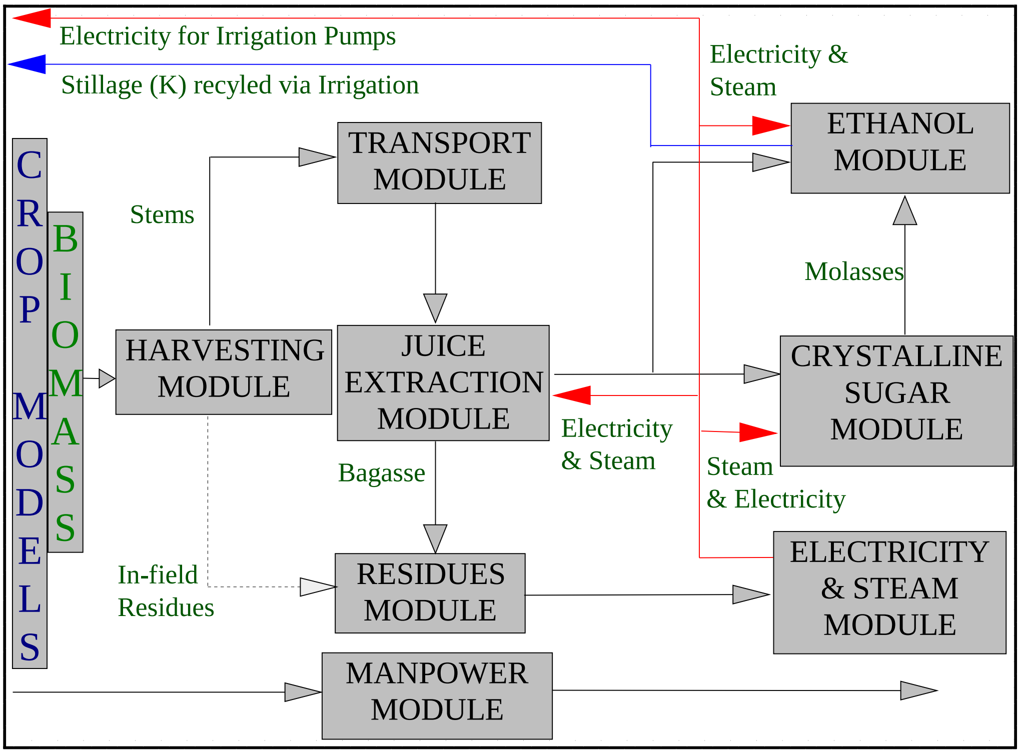

Fig. 2 Overview of Production & Conversion Processes within the Agrosystems Integration Package (AIP)

The sensitivity of biomass energy systems to site specific factors is addressed within the AIP through a number of factors including soil, climate, available skills, capital costs, etc. Further development of the AIP would be necessary if it is to address fully all the factors listed below:

climate
soils
competition for resources (land and water)
transport infrastructure
transport distances from fields to processing centres
proximity to and capacity of the local electricity grid
demand for energy products
labour costs and available skills
technological capacity of local industry

national and regional energy policies and subsidies / taxes
potential impact of novel technologies
logistics
local issues e.g. planning permission, public acceptability.

In addition to these factors, an integrated sweet sorghum / sugarcane system adds an extra level of complexity to existing monocropping systems e.g. sugarcane only. Optimising the integration of sweet sorghum into the sugarcane agronomic and milling schedules requires temporal factors to be assessed such as the timing of the availability of fallow land for the planting of sweet sorghum and the period of availability of the mill during harvesting. In such complex systems, a systems analysis approach can be used to integrate the impacts of changes at each level, to provide realistic estimates of costs, microeconomics and environmental impacts (Tsuji *et al.*, 1994).

In summary, the AIP aims to demonstrate:

1) The application of a modular computer model, capable of assessing the impacts of the use of different agronomic, industrial and technical variables on the entire energy and sugar production system- this will be a decision support system for replication to other sites.
2) The techno-economic viability of the sorghum bioenergy system- including resource requirements and environmental impacts.
3) That sweet sorghum is agronomically suitable to be grown without disrupting current sugarcane agronomic schedules;
4) That existing sugarcane processing facilities are capable of processing sweet sorghum for the production of electricity and ethanol.[4]
5) Determine energy, carbon, nitrogen, and water balances, fluxes, and requirements.
6) That the coupling of mechanistic crop models with downstream process models can be used to provide practical answers to site specific problems.

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[4] The physical demonstration of the viability of using sugarcane processing equipment to process sweet sorghum has been investigated at Triangle Ltd.'s sugar mill in SE Zimbabwe (sections 3.3. and 4.4)

1.4.1. Modelling an Existing Sugarcane-based System

The AIP is a close coupling of two models i.e. agronomic crop models, and an industrial process chain model, with ease of use aided by a windows-based Graphical User Interface (GUI). It is being developed using the Triangle Ltd. (Zimbabwe) sugar mill as the model system. This mill is a medium sized sugar mill currently producing around 300 000 tonnes of crystalline sugar and just over 20 Ml ethanol per year from the processing of 2.5 million tonnes of cane making it an ideal candidate for this study (Wenman, 1999a). The use of the modified CERES-Sorghum crop model as an integrated part of the AIP allows realistic and dynamic estimates of the potential production of sweet sorghum biomass. The estimated sweet sorghum biomass can then be used within the logistical model of the sugar mill to assess its capacity to process the sorghum and produce bioenergy.

Triangle Ltd. was the first sugar mill to be established in Zimbabwe in the 1940's and is located in the semi-arid southeast Lowveld region of the country. Its total area under sugarcane, including cane from the shared Mkwasine estate, about 50 km from the mill, is 21 000 ha. Over the last two decades it has undergone a series of expansions, except during the severe drought period of 1991 to 1993 when all sugarcane production ceased.

Triangle provides a good model for assessing the impacts of new technologies as the expansion in capacity has been met by the addition of new technologies, whilst for the most part the older equipment has been maintained to protect the existing capacity. A second, but equally important reason that Triangle has been used for this analysis, is that in 1981 a 40 million litre per year anhydrous ethanol plant was commissioned. The plant produced ethanol for blending with petrol, with the blend being distributed nationally at a 12% (v/v) mixture ethanol:gasoline. The plant currently produces about 20 Ml per year of potable ethanol depending on the availability of molasses, primarily for export to the EU. There is therefore considerable spare capacity to raise ethanol production back up to the rated capacity of 40 Ml per year, provided a supplementary supply of fermentation feedstock can be found which doesn't affect existing crystalline sugar production.

The dynamics of the production and marketing of bioenergy by Triangle Ltd. since the 1980's provides an extremely good real-world background for this study and the development of the AIP. For example, during the 1980's, Triangle became a significant producer of bioenergy at the national scale, combining the sales of fuel-ethanol and occasional exports of electricity to the national grid, in 1994 exporting 11 300 MWh of bagasse-generated electricity. However, the low cost of oil on the world market, and the subsidising of the electricity price by the Zimbabwean government, has resulted in a complete halt in blending ethanol with petrol, and a decreased incentive to sell bagasse-generated electricity to the grid. Very recently (June 1999), Triangle has again been in negotiation with the government-owned electrical utility (ZESA) to renew its supply of electricity to the national grid. (Wenman, 1999b)

1.4.2. Agronomic Modelling

Over the last forty years or more, a wide range of crop models have been developed. These models vary in both their sophistication and application, ranging from a virtually 'generic' cereal-type model (DSSAT 3.5; Tsuji *et al.*, 1994) to highly process-based models at the leaf or even molecular level (WIMOVAC; Humphries and Long, 1995). The sorghum model which is currently integrated with the AIP is a revised CERES-Sorghum model, most recently developed by Gosse and his team at INRA (France). The revisions by Gosse's group aim to account for differences in sweet sorghum varieties (predominantly in canopy establishment) compared to the generic CERES-Sorghum model, originally developed for grain sorghum.

Crop modelling and its application to the AIP are discussed in detail in the results chapter, but it is important to realise that these models are the cumulative, multi-disciplinary work, of a large number of scientists covering a period of over 30 years. Furthermore, their use in the AIP allows a high degree of flexibility for future development, in terms of both crop types and outputs and represents a new role for mechanistic crop models. This new role in effect recognises that such crop models have graduated from being tools developed to help in the fundamental understanding of crop growth to being practical tools in understanding complete production and conversion systems.

1.4.3. Industrial Modelling

The lessons from the development of crop models, in terms of an increasing detail not necessarily resulting in increased predictive accuracy, have been applied to the industrial conversion area of the AIP as discussed in section 1.5.2. (Sinclair and Seligman, 1996). In order to decide on the level of detail required in modelling the industrial processes which are involved in the processing of sweet sorghum, only the parameters directly relevant to the evaluation of bioenergy production have been used. Thus, for example, detailed thermodynamic models of gas turbines and combustion processes which have been developed elsewhere e.g. the ASPEN process models (Ogden *et al.*, 1997), but have not been coupled to the AIP. Within the AIP, the parameters which are important are the overall conversion efficiencies, electricity production capacity, manpower requirements, and installation and O&M costs. Specific equipment e.g. for juice extraction or bagasse combustion, should function to specification at any location and so models incorporating the detailed dynamics of these technologies are not required within the AIP. Therefore, unlike the agronomic area of the AIP where site specific factors are important and mechanistic models are needed, they are not used in the industrial conversion area of the AIP.

1.4.4. Barriers to Implementation

Apart from the evaluation of agronomic and technological risk (as discussed above) a number of other barriers to the implementation of the integrated sorghum / sugarcane system exist. The AIP can also be used to help assess these technical and non-technical barriers. A brief list of the barriers to the implementation of the proposed integrated sorghum / sugarcane system is given below, and these barriers will be evaluated in more detail in the Results and Discussion chapters.

Barriers include:

1. Logistical
2. Increased cropping intensity of 2 similar crop types:
    a. pests & diseases
    b. inputs (water, nutrients, manpower, pesticides, energy, etc.)

c. management

3. Institutional and Market Barriers
4. Technological
5. Availability of Land
6. Demonstrating carbon-neutrality

The AIP can be used to address these barriers in a number of ways. For example, the logistical and technological barriers to implementation can be evaluated by using the AIP to calculate the potential production of total biomass and products at a given time. Thus the mill capacity and processing rates required can be predicted and evaluated if the available land area is known. Alternatively, the land area required to meet the capacity of specific equipment can be evaluated. The results of increased cropping intensity can also be evaluated in terms of inputs and management requirements. However, a rigorous quantitative analysis of the likely impact in terms of pests and diseases is not possible as it would be limited to an extrapolation of existing data obtained from field trials.

Finally, because the AIP provides the framework for an entire processing chain on a site-specific level, it can be developed for use in providing energy, carbon, nitrogen, manpower, etc. balances. This in-built flexibility should mean that the AIP is applicable to a wide range of future implementations, strategies and sites.

1.5. Literature Review

An overview of the main literature sources is provided below. The review is broken down into the main subcategories which cover a complete sweet sorghum and sugarcane processing chain i.e. from land preparation for planting, through to the production of ethanol and electricity. Further background information is available through the author's sorghum website (www.kcl.ac.uk/links/sorghum.html) which contains links to other information resources on the Internet.

1.5.1. Sweet Sorghum Agronomy and Use

The most comprehensive and up to date information on sweet sorghum agronomy and use is undoubtedly the excellent Proceedings of the First International Conference on Sweet sorghum, held during September 1997 in Bejing, China. These proceedings are important, not least because they contain papers covering the considerable body of research carried out on both the breeding and processing of sweet sorghum in China which have been translated into English. See for example, Li's paper, 'Developing Sweet Sorghum to Accept the Challenge (of) Problems on Food, Energy and Environment in 21st Century' to provide a good overview of the proceedings. (Li, D., 1997).

The research carried out in Europe by the European Sweet Sorghum Network is well summarised in the Proc. 1st European Seminar on Sweet Sorghum, which also includes papers covering the growth and processing of fibre sorghum for paper manufacture (Gosse, 1996). More information can be obtained from the individual project publications and reports from the various European Union projects funded through its JOULE II, APAS, and FAIR programmes. However, much of the relevant EU research project work is published in the proceedings of the ten (to date) EU Biomass Energy Conferences which provide an invaluable information source on predominantly European based research. For example, see Kopetz (1998) The four (to date) 'Biomass Conferences of the Americas' have had less emphasis on sweet sorghum specific literature but provide useful information on conversion technologies, marketing and policy related issues. See for example, Overend and Chornet (1999). Details on how to search for and obtain relevant EU information can be obtained through the European Union Commission's documentation database web-server 'CORDIS' (www.cordis.lu).

Much of the work discussed here and either carried out directly or monitored by the author is available through the individual research project final reports:

1. EU funded JOULE II project 'Bioethanol Production From Sweet Sorghum: Interchange of Research and Experience Between EU and Developing Countries (Zimbabwe and Thailand). Contract No. JOU2-CT92-0232, Woods *et al.*

(1995).

2. EU funded PECO project 'Extension to Romania. Bioethanol Production From Sweet Sorghum: Interchange of Research and Experience Between EU and Developing Countries (Zimbabwe and Thailand). Contract No.CIPDCT93-0311. Hall *et al.* (1995).
3. EU funded APAS project 'The Production of Electricity And Biofuels Through The Integration of Sweet Sorghum Into The Sugar Industries in Developing Countries. Project No. RENA-CT94-0040. Woods *et al.* (1997).
4. Common Fund for Commodities (CFC) funded project 'Demonstrating Increased Resource Use Efficiency in the Sugar Industry of Southern Africa through Environmentally Sustainable Energy Production.' Contract No. CFC/ISO 13. Woods *et al.* (1999).

The reader is also referred to Doggett (1988) for a detailed analysis on the history of development of sorghum and its taxonomy. Practical information on the selection of sweet sorghum varieties, genetic and germplasm information, and growth and management, particularly for controlling of pests and diseases is available on-line from these web sites:

FAO Global Plant & Pest Information System (the unfortunately named 'GPPIS): http://pppis.fao.org (Sweet Sorghum crop code: SOBIC)

US- Agricultural Research Service Germplasm Resources Information network (ARS-GRIN): http://www.ars-grin.gov (Sweet Sorghum varieties and germplasm + accession info)

The USA Sorghum-Growers Association: www.sorghumgrowers.com (primarily grain sorghum in the US)

Information on global or national production can be obtained on line through the excellent FAO Agricultural Production Database: http://apps.fao.org (FAOSTAT Agriculture Database).

Whilst it is accepted that many 'on-line' resources do not have the longevity required for quoting as literature resources the URL's shown above are becoming the major interface between the organisations providing the data and the public. The nature and size of the organisations behind these internet-hosted information databases makes it highly unlikely that the URLs will be come 'broken links' for the foreseeable future.

1.5.2. Crop Modelling

Overview of Crop Modelling is predominantly based on papers contained in an Agronomy Journal Special Issue (1996, 88:)

Models fall between two types:

1. Full mechanistic (reductionist) models are developed for research purposes.
2. Empirical (statistical) practical problem solving

A considerable debate has been continuing for at least the last decade concerning the utility of using crop models away from the environment in which they were developed and calibrated. The argument is based around the inevitable need to use empiricisms at some level in crop models in order to control their complexity and the volume of input data required to make a model-based prediction. Indeed the concept of 'minimum data sets' has developed from crop modelling. As Sinclair and Seligman (1996) states, "Many of the biological coefficients needed to describe critical cultivar characteristics required complex experimentation. Inevitable experimental error in these coefficients (was) propagated and usually compounded through the model." This had led some researchers to conclude that mechanistic crop models may never be capable of providing good management advice to farmers or reliable crop production predictions to policy makers. In fact, Passiura (1996) states "It is hard to see a useful role, other than self-education, for models that fall between the scientific and the engineering types."

Other developers of crop models have remained more optimistic that crop models can achieve a realistic balance between compounding complexity and superficial simplicity. As Montieth (1996) states, the current debate about crop modelling "would have been approved by Aristotle, who argued that 'a well-schooled man... searches for that degree of precision ... which the nature of the subject at hand admits' (Nicomachean Ethics, Book 1, Chapter 3). If we took this advice seriously, we would put all our crop models on hold until we could describe (i) the principles and processes that govern the distribution of assimilates to different organs according to developmental phase and (ii) the uptake of water and nutrients by roots in relation to their growth, anatomy, and activity."

With the knowledge in mind that outside specific research niches increasing complexity both in the mechanisms embodied in the programme code and the number of input variables (such as soil and climatic parameters and crop genetic factors) must be managed and kept to a workable limit, the CERES models have continued to evolve (Hoogenboom *et al.*, 1999). As Passioura (1996) states, "it is notable that the well-established CERES family of crop models, which are predominantly functional rather than mechanistic, implicitly favour a sink limited scenario (feedback sensor mechanisms) in that they relate transpiration and growth to soil water content rather than to leaf water potential."

For the purposes of the AIP the CERES approach is the most useful in that predictions of yield are required at the field level. However, care must still be taken when using the results of such crop models. One of the main reasons for caution in interpreting the results of the models is discussed by Boote *et al.* (1996a), who states, "few crop growth models address effects of pests such as nematodes, air-borne and soil-borne diseases, and insects. We highlight this as a caution to those who too quickly or too optimistically propose that models should be able to account for most yield variations in the field."

Therefore, when combined with the knowledge that in-field variations in crop yields are often extremely large (Passioura, 1996), the AIP should only be used in the first instance to highlight the potential for the introduction of sweet sorghum. Further confidence in the predictive capabilities of the AIP for providing reliable estimates of yields would need to be confirmed through a process of on-site 'validation' through on the ground field trials.

Given Windows 95 type User Interfaces and modern programming tools the ease-of-use of modern computer-based models has improved considerably. This type of modern

interface is very well demonstrated in the WIMOVAC (Windows Intuitive Model Of Vegetation response to Atmosphere and Climate Change) model much of which can be accessed on line through a dedicated website i.e.
http://www.life.uiuc.edu/plantbio/wimovac/cabios.htm
The WIMOVAC model was developed by Humphries and details can be obtained either through the website or through literature e.g. Humphries and Long (1995).

Currently, the most advanced work on sweet sorghum-specific modelling is being carried out by Gosse's group at INRA's Institute of Bioclimatologie, France. Some of the modelling work is available in English through the literature and can be found in the Proc. 1st European Seminar on Sweet Sorghum held in Toulouse in 1996. Work on the more generic CERES-Sorghum model is available through the DSSAT literature which provides details on all aspects of the CERES crop models (Hoogenboom *et al.*, 1999; ICASA, 1998; Tsuji *et al.*, 1994).

1.5.3. Commercial Sugarcane, Sugar and Ethanol Production Data

Triangle Ltd. Operational data is primarily derived from weekly performance tables produced by Triangle Ltd to monitor their operating performance. This data was supplemented by computer based spreadsheets summarising various operating characteristics of the plants and was kindly provided by C. Wenman, D. MacIntosh, D. Siwela, and E. Bresler, but is not published material.

Calculation of thermodynamics, which requires the temperature and pressure of superheated steam to be known, then calculating the energy density of the steam was carried out using computer software developed by Moran and Shapiro (1991). The alternative was to use steam tables allowing the densities of steam in the supersaturated phase to be looked up and was backed up by the 'Steam Load Overall Balance' runs (Hoekstra, 1997). More recently, Matthews (1999) completed an MSc thesis on the potential for improvements in the use of bagasse as an energy resource at Triangle Ltd. and confirms that there is a significant potential for electricity production for export to the national grid.

More general information on the state-of-art in the sugarcane industry was obtained through various proceedings, but particularly through the Proceedings of the ‘Sugar 2000 Symposium,’ held in Brisbane, Australia, during August 1996 (Keating and Wilson, 1997).

At the global level, the issues involved with the marketing of ethanol have been exhaustively explored by Berg (1998a+b), in particular highlighting the difficulties ahead for the ethanol industry in creating a free and fair world ethanol market.

The dynamics of the production of sugars by sugarcane is discussed in detail by Cackett and Rampf (1981) in a paper which analyses potential changes in sugarcane management required to maximise ethanol rather than sucrose production. Data on sweet sorghum was obtained primarily through experimentation as discussed in Section 3, ‘Materials & Methods’.

1.5.4. Renewable Energy (Biofuel) Technologies

A very important overview of the current status of renewable energy technologies and their potential to supply the world with energy was produced in 1993 by Johansson *et al.* in the widely quoted ‘Renewable Energy: Sources for fuels and electricity’ with this book becoming known as the ‘Blue Bible’ by many in the Biomass Energy business. Despite becoming slightly dated now, even though reprinted in 1996, this is still the most exhaustive evaluation of the potential for modern renewable energy technologies to supply significant amounts of energy to the world both now and in the future. In particular, it highlighted the potential for biomass energy systems being coupled to the as yet not-fully-demonstrated gasification / gas turbine systems (Johansson *et al.*, 1993).

The use of gasification to increase the efficiency with which electricity is generated in sugarcane mills is based purely on data gathered from literature. However, no closely coupled gasifier / gas turbine systems have yet been installed in any sugarcane mill and the technology is still in its infancy. A tightly coupled gasification / gas turbine system has now been demonstrated for the first time at Värnamo, Sweden and other demonstration projects are now under construction (Ståhl *et al.*, 1997). This is a very rapidly developing subject, but currently, the most up to date reference material is provided through the proceedings of the Conference on "Biomass Gasification & Pyrolysis: State of the Art and Future Prospects" held in Stuttgart from 9th to 11th April 1997 (Kaltschmitt and Dinkelbach, 1997). The proceedings from this conference have been used extensively to supply relevant data for assessing the potential impact of installing a gasification system in Triangle Ltd. (Beenackers and Maniatis, 1997).

However, as no sugarcane bagasse using gasification system is yet in operation, the analysis of Bauen (1999) has been relied on as his work has involved an in depth assessment of the potential role of gasification in the sugarcane industry in Brazil.

Finally, much of the author's early exposure to the potential of gasification systems for biofuel production was in studying the potential for these systems in Brazil, both in the sugarcane and forestry industries (Carpentieri *et al.*, 1993). Since then, Carpentieri's work in Brazil has continued and a large-scale demonstration project is about to enter its construction phase, based on the use of dedicated forestry wood production (Waldheim and Carpentieri, 1998).